Positioning Eye Fixation and Vehicle Movement: Visual-motor Coordination Assessment in Naturalistic Driving

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Abstract

In recent years, many driving studies in the traffic safety literature have undertaken error assessments of driver behaviour. However, few studies have been able to analyse the detailed individual vision and motor behaviours of drivers, due to the lack of reliable data and available technologies. Therefore, little is currently known about drivers' visual-motor coordination involving the use of visual information to regulate their physical movements. This research sets-up a technical framework to investigate on-road drivers' visual-motor coordination via vision tracking and vehicle positioning. The driving behaviour and performance were recorded and analysed using Eye Movement Tracking, Global Navigation Satellite System (GNSS) and Geographic Information Systems (GIS). The eye tracker recorded eye fixations and duration on video images to analyse the visual pattern of individual drivers. Real-time kinematic (RTK) post-processing of multi-GNSS generated vehicle movement trajectory at centimetre-level accuracy horizontally, which encompasses precise lateral positioning, speed and acceleration parameters of driving behaviours. The eye fixation data was then geocoded and synchronised with the vehicle movement trajectory in order to investigate the visual-motor coordination of the drivers. A prototype of implementation of the framework focusing on complex U-turn manoeuvre at a roundabout in five older drivers was presented in this paper. The visualisation of spatial-temporal patterns of visual-motor coordination for individual drivers allows for a greater insight to behaviour assessment. The on-road driving test in this study has also demonstrated a discriminant and ecologically valid approach in driving behaviour assessment, which can be used in studies with other cohort populations.

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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 psychomotor abilities (Anstey, Wood et al. 2005; Molnar, Charlton et al. 2013). Several reviews of driving research have reached the same conclusion: when and where drivers look is of vital importance to driver safety (Underwood, Chapman et al. 2003; Lee 2008). The information that a driver uses is predominantly visual (Sivak 1996). Crundall and Underwood (2011) addressed that the driving task is eminently suited to the application of eye tracking methodologies, and a wide range of specific driving behaviours, from navigation to anticipation of hazardous events, are primarily dependent on the optimum 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 fixation of the tangent point when negotiating a curve (MacDougall and 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 and Underwood 2011). Therefore, the use of eye tracking measures has greatly increased the understanding of how driving skills develop and what strategies drivers employ to ensure a safe journey (Underwood, Chapman 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 supply of his/her environment, where the vehicle’s desired path served as guidance information, and at the same time deduce the vehicle’s actual motions related to its desired path which is served as stabilization information. According to both types of information, Donges further stressed that the driver has to intervene in order to keep the vehicle’s position continuously in the vicinity of its desired path. Hence, steering a vehicle is a control process with the desired path as forcing function (i.e. the road centreline) and the vehicle’s position and attitude relative to the forcing function as output variables. During driving, eye movement and steering are tightly linked (Chattington, Wilson et al. 2007), in other words, the speed control and lane alignment reflect the driver’s capability of using 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 horizontal curves (Fitzsimmons, Nambisan et al. 2012), understanding the visual-motor coordination becomes important to promote safe driving, in particular, for the cohort population of older drivers who have been in the area of high priority related to the increasing elderly population and higher involvement in the car crashes (Lee 2003; Rakotonirainy, Steinhardt et al. 2012), since aging might cause functional decline in vision and motor skill, adversely affecting driving behaviours and performance (McKnight 1999; Fancello, Pinna et al. 2013; Wood, Horswill et al. 2013; Sun, Xia et al. 2014).

Previously, on-road testing, computerized tasks, driving simulation, and clinical measures (physical, visual, cognitive) have all been used to estimate driving competency (Odenheimer, Beaudet 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 competency, it generally lacks of standardization and data on reliability or validity (Odenheimer, Beaudet et al. 1994). Many on-road driving assessments have only a pass or fail outcome that was based on driving evaluators’ clinical reasoning and not on a quantifiable, numerical test score (Shechtman, Awadzi et al. 2010). As Porter and Whitton (2002) postulated that a standardized on-road driving assessment with a quantifiable score based on Global Positioning Systems (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 and Charlton (2013) as future effort upon the DOS (Driving Observation Schedule) approach.

Nevertheless, few driving studies to date have been able to scrutinize detailed individual vision and motor behaviour data (such as speed and acceleration patterns in conjunction with visuospatial skills) due to the lack of reliable data and available technologies. Thus, little is known about drivers’ visual-motor coordination in different manoeuvres and the underlying neuropsychological mechanisms. For such reason, we hypothesize in this study that eye tracking technology when coupled with vehicle movement tracking provides an even more detailed assessment of an individual’s driving behaviour than standard on-road test. The goal of this paper is to propose a technical framework and to develop methods to study the visual-motor coordination in naturalistic driving, thereby forming a bridge between the literature on visual searching and motor control in driving research.

In this paper we present a framework of driving behaviour study using the combination of eye tracking and GNSS vehicle movement tracking in naturalistic driving. The on-road driving was recorded and analysed using eye tracking synchronised with multiple Global Navigation Satellite System (multi-GNSS) tracking, and Geographic Information Systems (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 real-time kinematic (RTK) postprocessing technique recorded and processed the precise vehicle movement trajectory, from which we detected lane keeping, speed control parameters of driving behaviours in GIS (figure 3). Previously, in an explorative pedestrian navigation study ETHZ (Kiefer, Straub et al. 2012) combined GPS (Global Positioning System) positioning with a gaze-overlayed video, however, they came cross GPS inaccuracy occurring in urban areas and present in their data. This is the first attempt in the research domain by the time this draft finished, which using surveying technology combining eye tracking to study human behaviours in a naturalistic setting. We investigated the visual perception pattern of the drivers and linked to their speed control and lane keeping, and analysed the discrepancies between individuals and groups. The objectives of this paper are as follows:

- To setup a technical framework which combines eye movement and vehicle movement data to investigate the visual-motor coordination pattern in the drivers.
- To implement above methods in a prototype: the visual-motor coordination of U-turn manoeuvre at a roundabout in older drivers.

2 A Framework of Combining Eye Tracking and Vehicle Movement Tracking in Driving Behaviour Assessment

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 their eyes are shifting from one location to another (Poole and Ball 2006). Over the past decade, eye tracking with highly specialized eye wear equipment has been used to record detailed and accurate eye movements and visual direction in many psychology studies (Gilland 2008). Kiefer and his colleagues from ETHZ studied self-localization and human wayfinding using location-aware mobile eye tracking (Kiefer, Straub 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 has 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, Dahlman et al. 2008; Dukic and Broberg 2012). Eye tracking enables the researcher to collect data relating to cognitive processes employed while undertaking any particular task such as turning, these processes may include the order and length of time a viewer directs gaze at any particular object in a visual scene (Falkmer, Dahlman et al. 2008). Fixation is a central aspect of eye tracking analyses, and may be defined as the length of time the eye ceases movement and remains set on any particular focal point (Green, 2002; Zwahlen & Schnell, 1998). Fixation is relatively "stationary" eye behaviour, which allows eyes to focus their gaze on the objects being looked at, and to extract this information (Yang, McDonald et al. 2012). 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, this method utilizes eye tracking to gain an accurate picture of a driver's visual pattern and can be used to evaluate driving behaviours.

2.2 GPS/GNSS Tracking Vehicle Movement in Driving Assessment

It can be comparably low-cost and ecologically valid to assess driving behaviours using Global Positioning System (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 can provide a means to assess driving behaviours by tracking vehicle movements (Porter and Whitton 2002; Grengs, Wang et al. 2008; Naito, Miyajima et al. 2009; Cruz, Macías et al. 2013; Mudgal, Hallmark et al. 2014). A Multi-GNSS (Global Navigation Satellite System) receiver is the system able to calculate position, velocity and time by receiving the satellite signals broadcasted from multiple satellite navigation systems. Currently, there are a number of GNSS systems under operating including GPS, GLONASS, Galileo, QZSS and Beidou (Kubo, Hou et al. 2014; Noomwongs, Thitipatanapong et al. 2014). Using multiple satellite systems can achieve high position accuracy with increased number of satellites compared to GPS-only positioning, particularly in harsh environments (urban canyon etc.) where the GPS-only positioning becomes difficult (Kubo, Hou et al. 2014; Noomwongs, Thitipatanapong et al. 2014). Due to the nature of satellite signals, GNSS raw data contains noises. The accuracy of GNSS data depends on many factors, the position of the satellites at the time the data was recorded, errors in satellite clocks and orbits, the trips through the layers of the atmosphere, and many other sources contribute inaccuracies to satellite signals by the time they reach a receiver (Sun, Odolinski et al. 2014). For such consideration, the relative GNSS techniques can be introduced to improve the accuracy by minimising the effect of each error source. The most complex relative technique is RTK (real-time kinematic) GNSS, which uses a known position of a base station to computer the moving receiver position. By having the base station over a known position, the errors of atmospheric effects can be estimated and referenced to the observed position of the receiver. This allows for relative positioning accuracies of sub-meter level and even down to decimetre level. From there, vehicle speed, acceleration/deceleration and lateral position data can be generated from the trajectory positions for driving behaviour assessment.

2.3 Combining Eye Tracking and Vehicle Movement Tracking in Driving Behaviour Assessment

Where and how long and how often the driver gazed at during driving are indicative of the visual perception strategy for the drivers to keep the car in an optimal lane position, in fact, cognitive resources involving visuospatial and motor coordination are required for driving manoeuvres. To investigate the visual-motor coordination in driving, the eye movement tracking can be integrated with the vehicle movement tracking by synchronising the two datasets. Figure 1 below illustrates the structural framework of such approach.

The eye tracking data including the fixation objects and duration of visual searching behaviour can be geo-coded using vehicle position reference, and linked to the parameters on vehicle movement trajectory, such as speed, acceleration/deceleration, vehicle head angle and vehicle lateral position to the road centreline (Table 1). Such data including 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 and synchronising can be accomplished in GIS (Geographic Information Systems) environment; the outcome dataset is presented in table 1. The (x, y) coordinates of the visual-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 visual-motor can be investigated in depth. A prototype implementation of the framework in next section presents the procedure and methods to further investigate the older drivers' visual-motor coordination of U-turn manoeuvre at a roundabout.

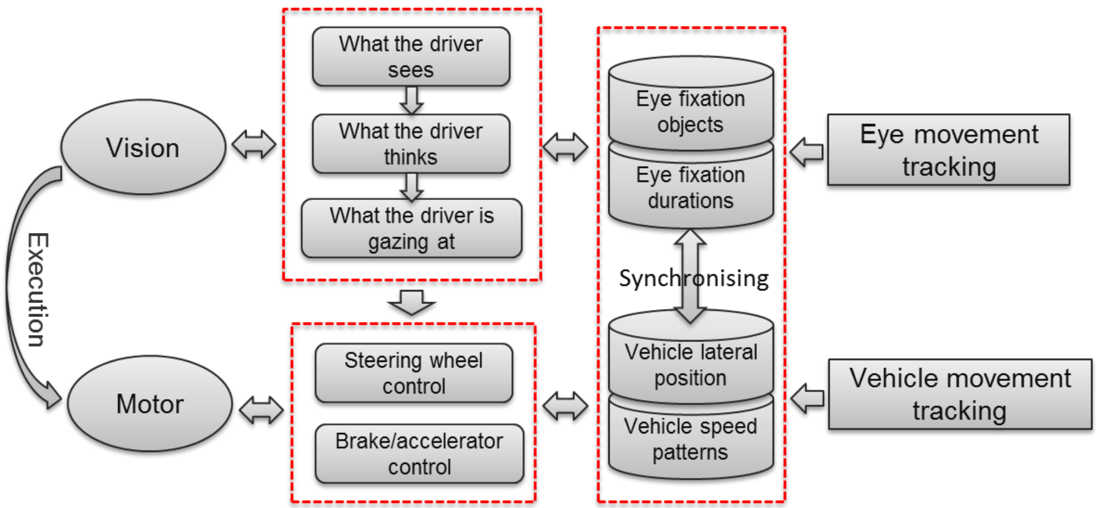

Figure 1: The combination of eye tracking and vehicle movement tracking to assess visual-motor coordination in driving: a technical framework

Table 1: Sample geo-coded eye movement records linked to driving behaviour parameters: the core dataset for visual-motor coordination analysis

		Parameters of Eye movement						**Parameters on vehicle movement trajectory**					
FID	Participant_ID	Fixation_no	Duration (second)	Background	Object	Gazing direction	Traffic	Speed (km/h)	Acceleration/deceleration (m/s)	Lane Deviation (cm)	Stages at Roundabout	X_coordinate	Y_coordinate
1	009	4082	0.2999	126	2891	Left	1	25.28	7.02	42	Before	394830.708488	6459223.656460
2	009	4084	0.2001	126	2892	Left	2	24.65	6.85	40	In	394830.626771	6459223.977120
3	009	4086	1.5992	126	259	Left	1	24.01	6.67	36	In	394830.495008	6459224.387060
4	009	4088	0.1666	126	243	Middle	2	23.25	6.46	30	In	394830.343245	6459224.904340
5	009	4090	0.2332	129	2892	Right	2	23.01	6.39	25	In	394830.150961	6459225.503240
6	009	4092	0.1667	126	2892	Right	2	23.00	6.39	22	In	394829.863753	6459226.237530

3 A Prototype Implementation of the Framework: Older Drivers' Visual-motor Coordination of U-turn Manoeuvre at a Roundabout

3.1 Participants and Recruitment

Previous studies found that older drivers were over-represented in angle collisions, crashes at intersections, turning and changing lanes (McGwin Jr 1999; Clarke, Ward et al. 2010; Marmeleira, Ferreira et al. 2012). Those evidences indicate that the age-related decline in particular function leads to unsafe driving (Dobbs, Heller et al. 1998; McKnight 1999; Fancello, Pinna et al. 2013; Wood, Horswill et al. 2013). Even so, not all older drivers are unsafe, the statistics don't reflect driving abilities of individuals; age itself, isn't the predictor of the fitness of driving (Anstey, Wood et al. 2005). While there is a strong emphasis around the world for older adults to maintain 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). Worldwide, the ageing population has brought the issue of older drivers into a sharper focus. In this case study, we set up on-road driving experiment in older drivers in order to investigate their visual-motor coordination behaviour.

Three female and two male older drivers aged from 60 to 79 (mean=67, SD =7.2) were recruited from 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 HREC (Human Research Ethics Committee), followed by an eye acuity check and the Mini-Mental State Examination (MMSE) to ensure their basic fitness for on-road driving. A mini-questionnaire survey on demographics and driving habits was also conducted prior to the assessment.

3.2 On-road Driving Test and Data Collection

The study area was chosen around the campus of Curtin University in Perth, approximately 1.5km radius distance from the Curtin GNSS (Global Navigation Satellite System) base station. This enables the 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 at the complex roundabout manoeuvres. This was achieved by simultaneously recording the driver's eye fixation and the vehicle movement trajectory.

During on-road driving test, participants were asked to drive their own cars with eye tracker mounted on their heads (Figure 2). A 16-point calibration procedure was carried out prior to the on road test. Eye-tracker: A head mounted Arrington Viewpoint TM eye tracker was used to measure the eye movements of participants in 60Hz. Data collected including number of fixations and fixation durations, a proxy to driver's attention and reaction to external stimuli from the environment are captured by the eye-tracker system. Corrected vision was required and the eye tracker can be worn with glasses when necessary. These processes may include the order and length of time a driver directs gaze at any particular object in a visual scene, as well as the visual patterns the driver utilizes while performing any particular driving task (Falkmer, Dahlman et al. 2008). The sequential video clips of drivers view and eye fixation objects (the green dots) in Figure 3 show 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.

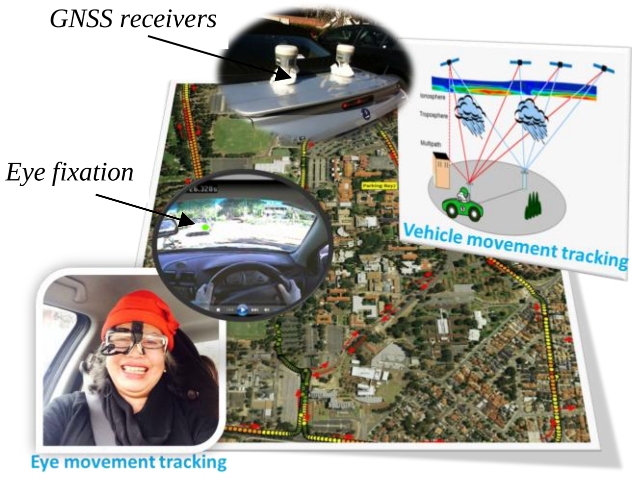

Figure 2: Equipment and on-road driving setting

A pair of Trimble R10 GNSS receivers was mounted on each participant's car roof to record the vehicle movement trajectory (Figure 2). The receivers are able to track multi-GNSS systems beyond GPS only approach, this is essential for recording vehicle movement in urban area when the precise vehicle positioning and smoothest trajectory are required. The tracking configuration of Trimble R10 receivers was setup at 10Hz in order to record the car positions at every 0.1 second. Real-time kinematic (RTK) postprocessing technique was used to achieve centimetre to decimetre level horizontal accuracy by minimizing the effect of error sources transmitted between the satellites and GNSS receivers (Sun, Odolinski et al. 2014). The post-processed data was then mapped to calculate the lateral position, speed and acceleration. Figure 4 shows one diver's speed control (left) and lane keeping (right) at the roundabout manoeuvre: slowing down to stop when approaching the roundabout, keeping moderate speed in the roundabout and accelerating to exit the roundabout; the perpendicular red lines between the car position to the road centreline demonstrate the lane deviations of the manoeuvre, 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). Further analysis based on the speed and lane keeping data between the drivers can be seen in figure 6.

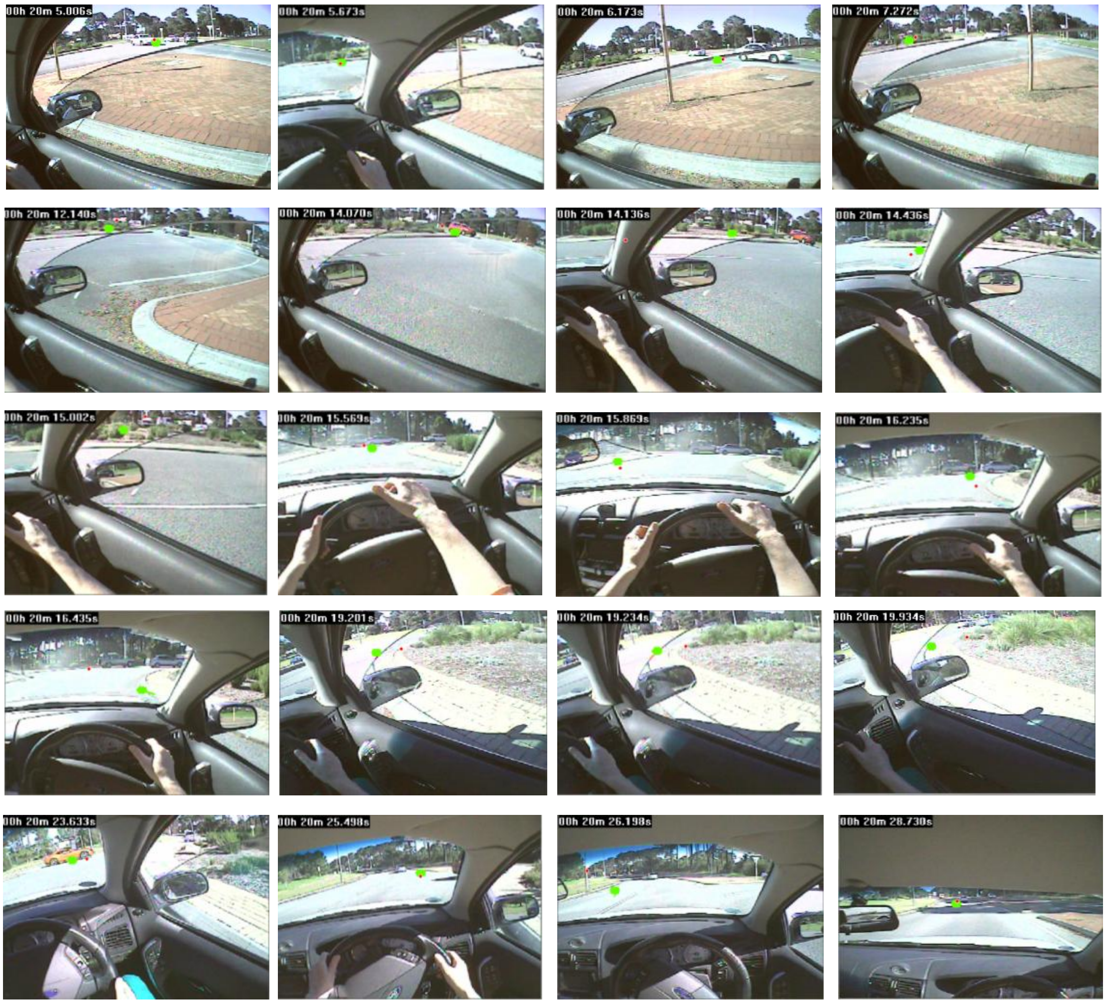

Figure 3: Video clips of driver's view and eye fixation objects recorded by eye tracker (left to right and top to bottom: the sequence of eye movement when taking U-turn through a roundabout, the green dots show the recorded right eye pupil fixation locations).

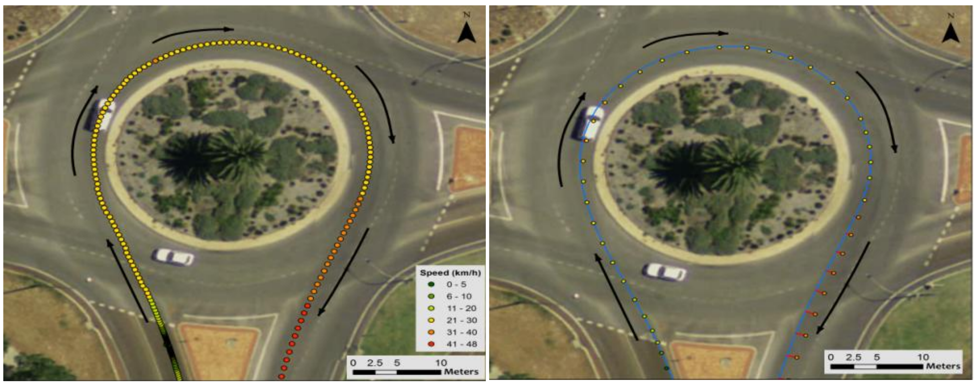

Figure 4: Patterns of speed control (left) and lane keeping (right) at a roundabout based on the multi-GNSS tracking vehicle movement trajectory (the blue line in the right map is the road centreline used as benchmark to calculate the lane deviation. The accuracy of the underneath orthoimagery is +/- 5m horizontally.)

3.3 Spatial-temporal Pattern of Visual-motor Coordination in Individual Drivers

All the five older drivers' manoeuvres were analysed in GIS platform, the core dataset 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 individuals.

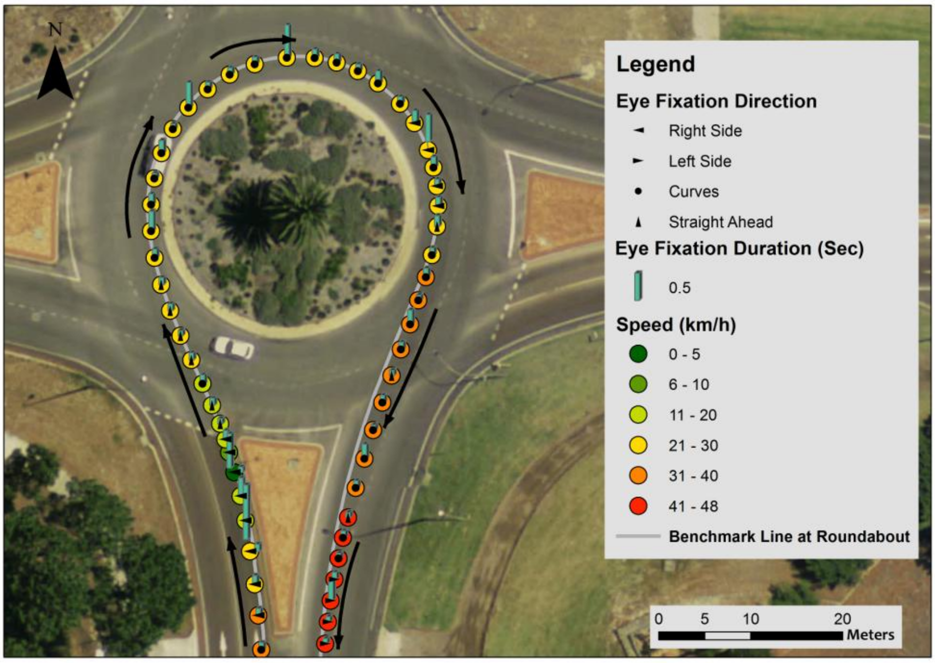

Figure 5: Positioned eye movement fixation behaviour and vehicle movement at a roundabout: A sample

As shown in figure 5 above, the driver smoothly decelerated when approaching the roundabout from 31-40km/h to 21-30km/h then to 11-20km/h to prepare to enter the roundabout and steadily accelerated through the roundabout and while exiting the roundabout to 41-48km/h. Eye tracking data shows 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 at the inner rear view mirror, 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 at tree or shrub, looked into the curve at trees/shrubs and line markings, and looked left at trees/shrubs. 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 would give more insight into the understanding of how the drivers used visual information to control their physical movement in particular manoeuvres.

3.4 Statistical Analysis of Visual-motor Coordination in Older Drivers

Figure 6 below shows the variations of visual-motor coordination through roundabout manoeuvres among 5 older drivers. The left graph shows the duration and numbers of fixations within individual drivers; and the right plots the mean and std of speed control and lane deviation. As can been interpreted, Driver4 had the most frequent eye fixation and longest duration at curves, presented the lowest lane deviation, and slight higher mean speed. Driver3 had the least frequent eye fixation overall but average eye fixation and duration at curves, this participant demonstrated the highest lane deviation but the lowest std (standard deviation) 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 curves seems associated with lane keeping and speed control, but there might be other conditions leading to the driving performance at roundabouts.

The descriptive statistical analysis in this case study tells that older drivers with 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, exiting 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 in order to detect the detailed behaviours which can be hardly observed by other methods, such as observation by instructors, clinical assessments or driving simulations, etc.

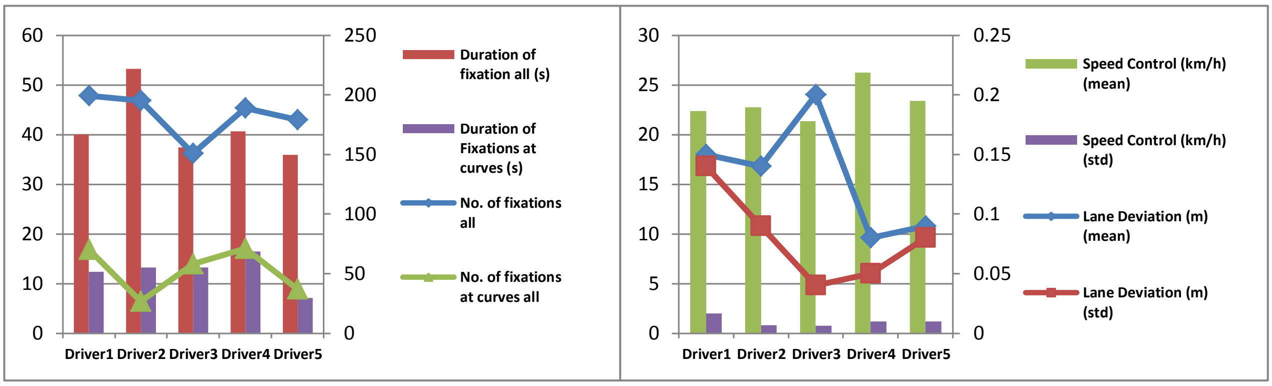

Figure 6: Visual-motor coordination at roundabout manoeuvres among older drivers (left: the duration and numbers of fixations within individual drivers; right: the mean and std of speed control and lane deviation)

In summary, this case study showed that combining eye tracking and precise vehicle movement tracking can detect the variation of the visual-motor coordination in older drivers. This study has also presented a cost-effective and ecologically valid approach in driving behaviour assessment, which can be used in studies with larger sample size in the future. Further advanced statistical analysis method, such as DFA (discriminant function analysis), can be used to predict variables affecting visual-motor coordination in older adults with high discriminant validity.

4 Discussion and Conclusion

In recent years, the behaviour of drivers has become one of the main objectives of safety research; much attention has been focused on the perception and cognition of the drivers. Several studies have shown that mental and physical conditions, driving habits and behaviour when performing certain manoeuvres differ between groups. For example, the mental and physical conditions of older drivers over 65 and their ability to concentrate behind the wheel deteriorate more rapidly; with the result that there is a greater likelihood of older drivers having crashes on the road (Fancello, Pinna et al. 2013). Underwood and Chapman et al (2003) found a different sequences of visual patterns between experienced and novice drivers, suggesting that it may be of benefit to provide suitable intervention/s for novice drivers. Similar interventions may be beneficial, for example, for drivers with autism and post-stroke drivers. Motivated by these considerations, more recent research has primarily focused on behavioural measures to assist driving in particular cohorts. These interventions have been aimed at facilitating certain tasks and improving their performance, so as to promote safe driving.

This paper presented a technical framework and methods for investigating drivers' visual-motor coordination in naturalistic driving using some advanced spatial tracking technologies. We simultaneously recorded drivers' eye movement and precise vehicle movement, 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 and investigated age-related changes in visual exploratory and driving manoeuvre behaviours associated with visual-motor coordination. This 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.

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 (RTK multi-GNSS) that was used ensures the accuracy 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 and from where a driver is viewing their surroundings, 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 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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