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Sensorimotor Basis of Motor Vehicle Control

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Abstract

Driving represents one of the most common modes of transport world-wide. It is also one of the major causes of death and injury in developed societies prompting technological innovations through which computers share or assume control of the task of driving, through a range of Advanced Driver Assisting Systems (ADAS). Given the lengthy and substantial investment in such systems it is perhaps surprising how little we understand about how humans control motor vehicles and why, on occasion, this control fails. This is actually a problem. Driver-assist systems that do not understand human drivers well can be dangerous and promote unforeseen risks. For example, anti-lock braking systems, which are designed to prevent skidding during heavy braking, do not always have the positive impact on safety one might expect (Farmer, Lund et al. 1997, Sagberg, Fosser et al. 1997), perhaps because their operation does not mesh seamlessly with the expectations of drivers or other road users.

One route to gaining a better understanding of the control processes employed by drivers, is through the study of situations in which standard steering strategies fail. In this thesis the studies are largely inspired by reports describing what happens during a lane change manoeuvre when visual feedback is temporarily removed. A typical lane change includes two phases, but when visual feedback is withheld, drivers repeatedly omit the second phase. In this thesis, we investigated this effect in a series of experiments aimed at getting to the bottom of the causes of this error. The thesis begins by seeking to generalize the effect from the special case of a straight road which was the focus of earlier studies. This was deemed important because a typical steering wheel has a natural tendency to re-centre itself. It is possible that this behaviour reduces the active steering movements a driver must make during a lane change, since they do not have to actively return the steering-wheel to the neutral position. For that reason, we designed a circular road on which a non-zero steering wheel angle was required at all times. Through this study, we were able to conclude that the effect does generalize.

In a second set of experiments we attempted to investigate which visual cues are essential for drivers to correct their error. Apparently, a normal road with redundant information provides sufficient visual feedback for drivers to make a lane change. However, it is of interest to know to what extent the visual feedback can be reduced and still meet the minimum requirement. In our study, we chose optic flow as a starting point. Optic flow has previously been shown to suffice for the purpose of heading perception and heading control. A number of ‘steering-towards-a-target’ studies also found that optic flow is tightly related to steering performance. Hence, we asked whether optic flow was sufficient for controlling a lane change manoeuvre and, unlike much of the previous studies on flow, we posed the question in an active steering task, revealing that flow alone is not sufficient to prompt correct lane changing behaviour.

In the concluding set of experiments we took our studies out into the field. Most previous studies on lane changing have been conducted in driving simulators. Simulators are limited in that they cannot provide complete vestibular information or the lateral forces associated with physical motion. Recently, research found that primates use both visual and vestibular feedback in an optimal way to achieve precise control of self-locomotion, hence it would not be surprising if drivers incorporate motion cues in the control of steering too. To test this possibility, we tested behaviour using an instrumented vehicle. Interestingly, even though drivers could complete the manoeuvre accurately in the real car (even without visual feedback) they continued to make the systematic error in the simulator (even in a motion platform). This strongly suggests that non-visual cues play a crucial role in the control process.

Overall this thesis advances our understanding of steering control in a number of ways. It is apparent that lane-change errors apply across multiple simulators and scenarios even when the driver is required to actively steer at all times. The work also reveals that optic flow information alone is not sufficient to motivate appropriate steering responses despite the ability of observers to accurately extract their heading from the flow information. And thirdly, the work suggests that non-visual cues generated by inertial forces, form an intrinsic part of normal lane changing behaviour, allowing subjects to perform the task even in the absence of visual information. This last result, in particular, should prompt theoreticians to include somatosensory and vestibular senses into their models of control, and cautions against over-interpreting results from simulator studies in which these cues are weak or non-existent.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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Publications during candidature

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Contributor	Statement of contribution
Author Xin Xu (Candidate)	Designed experiments (60%) Data Analysis (70%) Wrote the paper (70%) Collected data (10%)
Author Wallis	Designed experiments (40%) Data Analysis (30%) Wrote and edited paper (30%)
Author Cloete	Collected data (90%)

Contributions by others to the thesis

No contributions by others.

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None.

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Keywords

optic flow, driving, steering, lane change, vestibular cues, internal model, inertial feedback, real vehicle

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Table of Contents

List of Figures

Chapter 1 Introduction and Literature Review

Chapter 2 Study 1

Experiment 1

Experiment 2

Experiment 2 Appendix

Chapter 3 Study 2

Experiment 1

Experiment 2

Experiment 2 Appendix A

Experiment 2 --- Appendix B

Experiment 2 --- Appendix C

Chapter 4 Study 3

Experiment

Chapter 5 Study 4

Experiment

Experiment Appendix

List of Tables

Chapter 2

Experiment 1

Experiment 2

Chapter 3

Experiment 1

Experiment 2

Chapter 5

Experiment

List of Abbreviations

2D:	Two Dimensional
3D:	Three Dimensional
FoE:	Focus of Expansion
VD:	Visual Direction
FP:	Future Path
HMD:	Head Mounted Display
VR:	Virtual Reality
FFT:	Fast Fourier Transform
HoA:	Heading on Arrival
HC:	Heading Changes
Exp.:	Experiment
RR:	Return Ratio
RMSE:	Root Mean Square Error
ANOVA:	Analysis of Variance
GPS:	Global Positioning System

Chapter 1 Introduction and Literature Review

Optic flow and control of locomotion

For the vast majority of us, navigation through our environment forms a crucial part of everyday life. Even if, in our modern lives, feeding only require us to get from the lounge to the kitchen, we still need to do so without colliding with chairs and tables. There is plenty of hard computational work to be done, requiring sophisticated visual processing abilities, and yet we appear to be able to do so effortlessly. Because of the ease with which we navigate a wide range of environments (i.e. forests, hills, open landscapes, etc.), it has been argued that there must be certain fundamental visual cues available that support locomotion in any and all natural environments. In the 1950s, the concept of optic flow was introduced by Gibson (Gibson 1950, Gibson 1958). Optic flow describes the continuous temporal change of the optic array around a point (e.g. an observer) generated by the relative motion between the point and its surroundings. Gibson observed that during movement, an observer's position in space changes from moment to moment, resulting in smooth, diagnostic changes in the optic array around the observer, referred to as optic flow. Gibson proposed that optic flow can be used as a cue to locate one's instantaneous heading (i.e. direction of movement). Indeed, during forward translation in a stationary environment there is a still point in optic flow that indicates a person's instantaneous heading. Figure 1 shows that during an observer's forward translation toward the target (i.e. the green point), all images in optic flow except the target move in a way that the reverse directions of their motion converge on the target. Meanwhile, the target itself remains still and its image in the observer's retina expands during approach. This unique feature is only true of the "Focus of Expansion" (FoE) in the flow field. Obviously, one can navigate to a target simply by matching the location of FoE and the location of the target.

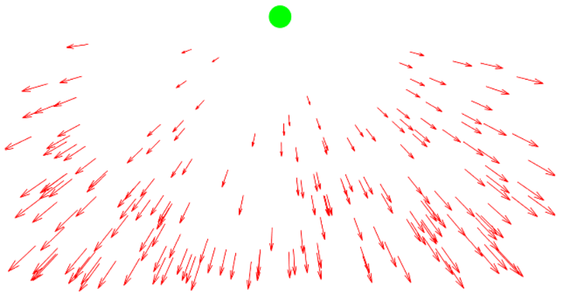

Figure 1 shows an example of "Focus of Expansion" (the green point) in optic flow during forward translation to the target (in this case, also the green point). Optic flow used in experiments usually consists of white dots distributed across a flat ground plane or distributed in 3D-space.

Since optic flow provides an efficient and elegant solution for regulating self-locomotion, many studies have been carried out attempting to test its role in navigation. It has been found that during pure forward translation, humans can locate their heading to within a couple of degrees (Warren and Hannon 1988, Warren, Morris et al. 1988, Foulkes, Rushton et al. 2013). Such accuracy is believed to be well within the range necessary for effective control of locomotion in various situations, such as walking, running, steering, etc. (Cutting 1986). However, pure forward translation is a rather idealized situation. A more common scenario is that observer moves with frequent eye movements (i.e. fixating something other than the target) and path rotations (i.e. a curved path). In this case, the pattern of optic flow is more complex than the one shown in Figure 1, with FoE differing from the true heading (Regan and Beverley 1982). If optic flow is to be used in this situation the observer needs to decompose optic flow into translational components and rotational components to ascertain their true heading. Researchers have since been debating whether optic flow alone is sufficient for resolving the rotational problem. Since rotation could be generated by either eye rotation or path rotation, these two root causes have been investigated separately.

First, for investigating the problem of translation with eye rotation, two typical test environments were created, both of which generated the same optic flow but different oculomotor signals. In one set-up, the observer was instructed to fixate a moving object during pure translational motion (real eye movements). In another set-up, the observer's fixation was stationary but the scene was generated by the camera (i.e. a virtual camera in a scene rendering program) fixating a static object during pure translational motion (simulated eye movements). In either set-up, the flow fields were a combination of the translation and rotation. However, in the former case the rotation was caused by the observer's own eye movements with oculomotor signals available, whereas in the latter case the rotation was caused by the camera with no actual eye movement. If optic flow is sufficient to do the decomposition, then one would expect observers to perceive heading equally well during real eye movements with an oculomotor signal, or simulated eye movements without an oculomotor signal. However, a large discrepancy occurred among work during 1990s. Mathematically, studies such as that by Perrone (1992) proved that it is feasible for the visual system to resolve the rotation problem, regardless of the availability of oculomotor signals. Practically, however, the agreement that observers can perceive heading accurately during translation with simulated eye rotation only occurred when the rotational rate was below 2 degrees per second (Warren and Hannon 1988, Warren and Hannon 1990, Royden, Banks et al. 1992, Van den Berg 1992, Van den Berg 1993, Royden, Crowell et al. 1994, Van den

Berg and Brenner 1994, Van den Berg and Brenner 1994, Banks, Ehrlich et al. 1996, Van den Berg 1996). With higher rotations (above 2 or 3 degrees per second), oculomotor signals appear to be essential for optic flow decomposition (Royden, Banks et al. 1992, Royden 1994, Royden, Crowell et al. 1994, Banks, Ehrlich et al. 1996, Ehrlich, Beck et al. 1998). The great disagreement in the literature on this issue was probably because this type of experiment created a cue conflict situation, in which the rotational components were caused by multiple sources (i.e. eye movements or a camera rotation). Participants in these experiments were struggling to find the root cause of the rotational components, especially when there was no eye movement. It was found that without real eye movements, observers often attributed the rotational components to the curvature of path despite the fact that there was only pure translation motion along a straight path (Royden, Banks et al. 1992, Royden, Crowell et al. 1994, Banks, Ehrlich et al. 1996). As a result, it was proposed that oculomotor signals are necessary for humans to perceive heading accurately in a situation of translation plus eye rotation (i.e. the direction of moving is not the direction of looking). Later, some follow-up studies found that although added optic flow layers (objects, texture, etc.) help observers to resolve the rotation problem with optic flow alone, the best performance is achieved when both optic flow and oculomotor signals are available (Li and Warren 2000, Li and Warren 2002, Li and Warren 2004), and more recent studies have become focused on modelling how visual cues and oculomotor signals are integrated (Saunders and Niehorster 2010).

Apart from translation with eye rotation, researchers also looked at heading perception during translation with path rotation. Compared to the complicated situation of eye rotation, path rotation seems to be a much easier task for the visual system, since from as early as the 1980s, studies consistently report that observers could accurately perceive heading with an accuracy of 2 degrees or less (Warren, Blackwell et al. 1991, Warren, Mestre et al. 1991, Stone and Perrone 1997, Li, Sweet et al. 2006, Li, Chen et al. 2009). The occurrence of such clear results might be due to fact that during the experience of circular motion participants were usually allowed to freely move their eyes (e.g. (Warren, Mestre et al. 1991)). With free eye movements, a cue conflict situation such as translation with simulated eye movements will not happen. However, interestingly, a recent study showed that even with simulated eye movements (i.e. camera fixating on a target different from instantaneous heading), observers can still accurately perceive heading during circular motion (Li and Cheng 2011b).

In addition to optic flow, researchers also explored other potential cues for the control of self-locomotion. In 1971, Llewellyn proposed that not only FoE can be a cue but also target drift (Llewellyn 1971). Target drift appears when the observer’s heading does not coincide with a fixated target. For example, the image of the target on the retina drifts to left side if an observer heads to the right side of the target (Figure 2, Left). That is, the occurrence of target drift indicates the current direction of movement is not leading to the target. Further, the direction to which the target drifts indicates the direction in which one must steer in order to reach that target. Essentially, target drift is very similar to the concept of visual direction which has been identified as a potential cue to heading control independent from optic flow (Figure 2, Right).

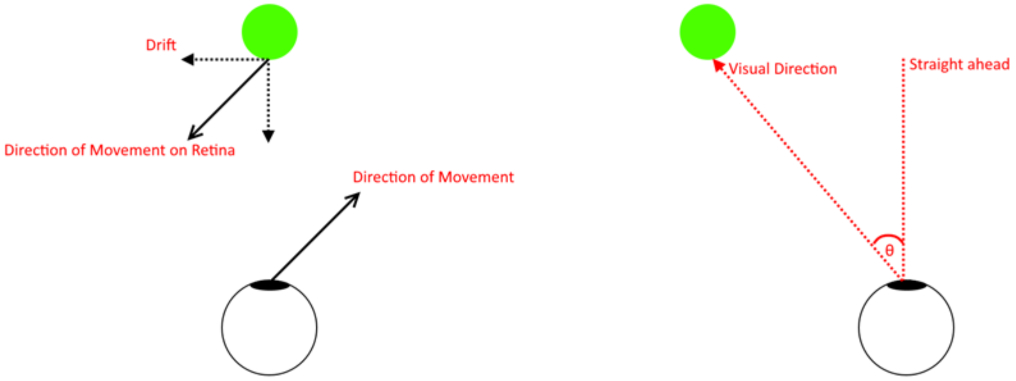

Figure 2 explains the concept of target drift (Left) and the concept of visual direction. The green point is either the target (Left) or fixation (Right).

Research has found that observers can successfully walk to a target by maintaining a constant visual direction with respect to a target. Close to twenty years ago, Rushton, Harris et al. (1998) conducted an experiment in which they asked participants to wear a pair of prism glasses and walk to a target. A prism creates an overall offset in optic flow but maintains its structure. Therefore, despite a lateral shift on the egocentric direction with respect to the target, the structure of optic flow and FoE remain intact. Because of this, one would expect to see participants going straight toward the target if they chose to align the FoE and the target. On the other hand, if visual direction instead of FoE is used, participants have to continuously adjust their locomotion direction in order to maintain a constant visual angle relative to the target, since the image of the target on the retina is constantly shifted. The results showed that participants walked towards the target on curved trajectories. Since curved trajectories are expected only if visual direction is used, Rushton et al. (Rushton, Harris et al. 1998, Harris and Rogers 1999, Rushton and Salvucci 2001) argued that humans rely on visual direction rather than optic flow to guide locomotion. Later, various follow-up studies confirmed that the visual direction cue plays an important role in guiding locomotion

(Wood, Harvey et al. 2000, Harris and Carre 2001, Warren, Kay et al. 2001, Harris and Bonas 2002). That said, researchers also found that in richer environments, consisting of textures, optic flow still plays an important role in locomotion, since observers walk toward the target on a much straighter path (Wood, Harvey et al. 2000, Harris and Carre 2001, Warren, Kay et al. 2001). It is by now widely accepted that humans probably combine both visual direction and optic flow to navigate (Wood, Harvey et al. 2000, Harris and Carre 2001, Warren, Kay et al. 2001, Wilkie and Wann 2002, Wilkie and Wann 2003, Wilkie and Wann 2005).

More recently studies such as those carried out by Li et al. (Li and Niehorster 2014) have sought to further clarify the relationship between visual direction and optic flow. In their experiment, Li et al. asked participants to steer a simulated vehicle toward a target in the face of random perturbations. Perturbations were designed in such a way that they either changed the vehicle's heading (affecting only FoE) or changed the vehicle's orientation (affecting only visual direction). During the experiment, the authors manipulated the richness of the flow field used (i.e. from sparse optic flow consisting of a few dots to dense optic flow consisting of many dots) and measured participants' responses to perturbations. The results show that for perturbations of a vehicle's orientation, participants demonstrated similar responses across all flow fields regardless of dot density. In contrast, for perturbations of a vehicle's heading, participants produced larger responses in denser optic flow environments. The authors also found that the delays of responses were significantly shorter for perturbations of a vehicle's orientation compared to that for perturbations of a vehicle's heading. From the results, they suggested that humans react more quickly to changes in visual direction. This is probably due the fact that visual direction is immediately available once the target is presented, whereas FoE is not available until relative motion happens. In light of this, the authors proposed that our visual system may process visual direction independently of optic flow.

After the discovery of the potential role of visual direction, a number of studies continued to question whether it is necessary to recover instantaneous heading (i.e. FoE) from optic flow to control self-locomotion. In 2000, Wann et al. claimed that it is possible to control steering without the retrieval of heading (Wann and Land 2000, Wann and Swapp 2000, Wann and Land 2001). Wann et al. proposed that humans can directly use retinal flow without decomposing it into translational components and rotational components. Retinal flow is derived from optic flow, and can be seen as a subset of optic flow. Retinal flow describes the temporal change of the optic array on one's retina. Theoretically, if an observer remains still, relative to the scene, there is no optic flow since the optic array around the observer does not change. In this case, even if an observer moves his/her eyes there is still no optic flow despite the fact that the image on the retina changes. This difference is due to the fact that optic flow is defined as changes in the optic array around the observer, whereas retinal flow is defined as any shifts in the retinal image. Thus, during eye movements the image on the retina changes but the optic sphere centred at the observer remains the same, hence the optic flow is, strictly speaking, zero. Unfortunately, despite the clear distinction in theory, in practice researchers use “optic flow” to refer to any change in the optic array (retinal image) caused by either eye movements or relative motion. From this perspective, optic flow is often equal to retinal flow. In this thesis, the term “retinal flow” is used only to emphasise eye movements during self-locomotion otherwise it shares the same concept as “optic flow”.

Wann. et al. (Wann and Land 2000, Wann and Swapp 2000, Wann and Land 2001) found that vertical lines are present in retinal flow along a line corresponding to ones’ future path (i.e. where you want to go) as long as the observer fixates his/her target while moving toward the target. In other words, the appearance of vertical lines in retinal flow along one’s future path indicate that the observer is accurately heading toward the target. On the other hand, the presentation of curved lines suggests that the observer is either understeering or oversteering with respect to the target. Further, the direction of curvature of those curved lines indicates the direction of steering error (i.e. understeering or oversteering). Taken together, the presentation of lines on retinal flow along one’s future path tells the observer whether he/she is on course. Wann et al. hence suggest that retinal flow can directly guide locomotion without the need for heading estimation. Unlike optic flow, in which researchers found it is possible to retrieve instantaneous heading even if the observer’s fixation is not on the target, Wann’s strategy, requires the observer to fixate the target during locomotion (i.e. look where are you are going). One advantage of such a strategy, as Wann et al. point out, is that it avoids overburdening the visual system with complicated decomposition of the optic flow (Wann, Swapp et al. 2000). Later, Wann and colleagues describe this strategy as “active gaze” or “future path” (Wann and Wilkie 2004, Wilkie and Wann 2006, Wilkie, Wann et al. 2008). Active gaze proposes that humans continuously pick up a goal 1 to 2 seconds ahead along the future path and directly use retinal flow to guide steering toward that goal. Studies conducted recently (Robertshaw and Wilkie 2008, Wilkie, Kountouriotis et al. 2010) suggest that active gaze not only guides locomotion but also influences locomotion. They found that if observers are required to gaze at a position they will show a tendency to steer toward that position. Together, active gaze suggests that observers often look where they are going, and likewise, observers also steer to where they are looking. This is not the end to the debate, however. A critical review of the future path theory was put forward recently by Li and colleagues (Li and Cheng 2011a). They conducted a study investigating participants' heading error profiles during steering toward a target. Their results showed that the predication of the future path strategy does not match the heading errors produced by their observers.

Models of heading control

In additional to the behavioural investigations into human navigation described above, there have also been attempts to develop a model of human navigation. Although visual feedback has dominated much of the thinking, some studies have also proposed that any control model should incorporate feed-forward[1] elements as well as other sensory cues such as vestibular information. In the following sections, we will review some popular models, with a specific focus on the issue of vehicle steering including areas in which the behavioural data described above has influenced current thinking.

Locomotion

Fajen, Warren et al. proposed a model to account for route selection behaviour in the presence of goal and obstacles, on the basis of instantaneous heading (Fajen, Warren et al. 2003, Fajen and Warren 2003, Huang, Fajen et al. 2006, Fajen and Warren 2007). In their model, an agent's behaviour is determined by a potential function controlling the agent's angular acceleration. The potential function can be generated via a linear combination of a function of the goal acting as an attractor, and a function of obstacles acting as repellers. By estimating heading and distance with respect to the goal and obstacles, the potential function can then determine where to steer. The earlier version of this model was developed for static obstacles and goals. Later, this model was extended to the case of moving objects as well (Fajen and Warren 2007). Interestingly, the difference existing between two versions suggest that humans may use two different strategies between steering to a stationary target and steering to a moving target. On the other hand, Wilkie, Wann et al. proposed a model to describe the trajectory when steering toward a target (Wilkie and Wann 2002, Wilkie and Wann 2003, Wilkie and Wann 2005, Wilkie, Wann et al. 2008). Unlike Fajen's model that emphasizes heading estimation, this model uses a function

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[1] A feed-forward control system responds to its signal in a pre-defined (i.e. anticipatory) way; It is in contrast with a system incorporating feedback (i.e. feed-back control system).

consisting of information from retinal flow, extra-retinal information (e.g. eye movement signals), and egocentric direction to determine which trajectory to steer.

Vehicle steering

There is considerable disagreement in the literature as to how drivers steer a vehicle. Earlier theories usually assumed that drivers have access to continuous, uninterrupted visual feedback and hence steer vehicles in a closed-loop[2] manner (McRuer and Weir 1969, McRuer, Allen et al. 1977, Reid, Solowka et al. 1981, Hess and Modjtahedzadeh 1990, Masaki and Ieee 1992, Modjtahedzadeh and Hess 1993). Godthelp (1985) investigated both closed-loop and open-loop[3] models in a basic lane change manoeuvre. In his study, feedback was removed for a brief period to test the role of continuous feedback. He found that with short periods of visual occlusion (1 to 3s), participants' lane change performance was comparable to that in the full visual feedback condition. One year later, Godthelp (1986) continued to investigate curve negotiation with constant visual feedback and with ~1.5s visual occlusion. Again, he found participants performed equally well with full or interrupted feedback. Godthelp concluded that drivers can tolerate a temporary loss of visual feedback during driving, with closed-loop control merely being used in a compensatory manner for steering. A follow-up study conducted by Hildreth, Beusmans et al. (2000) backed up this finding by showing that participants' lane correction performance was not degraded in the face of a 2s visual occlusion. However, just two years later, Wallis et al. found that drivers are actually unable to conduct a lane change without visual feedback (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007) – see Figure 3. Without visual feedback, drivers only turn the vehicle towards the destination lane (the first steering phase, see Figure 3) but never return the vehicle to the original heading (the second, return steering phase, see Figure 3), resulting in the vehicle going off the road in the direction of the lane change. This inconsistency among studies can largely be attributed to the different methodologies. Both Godthelp and Hildreth et al. 'turned the light on' immediately after the brief visual occlusion, allowing their participants see the result of their lane-change conducted with no visual feedback. Most likely, their participants learnt after a few trials and changed their behaviour. Indeed, Wallis et al. demonstrated that after several trials drivers are able to conduct lane change in darkness if feedback of their performance is provided at the end of each trial (Wallis, Chatziastros et al. 2002). Recently, Zhao and Warren attributed this failure to the longer visual occlusion used in Wallis et al.'s studies (Zhao and Warren 2015). Based on

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[2] Closed-loop refers to feedback control, in which feedback is incorporated to respond to the input signals.

[3] Open-loop refers to feed-forward control.

the results from this thesis, as well as other previous studies, we would argue that a typical lane change cannot be done within just 2 seconds (which was used in previous studies). Consequently, longer visual occlusion was required to ensure participants had enough time to conduct this manoeuvre.

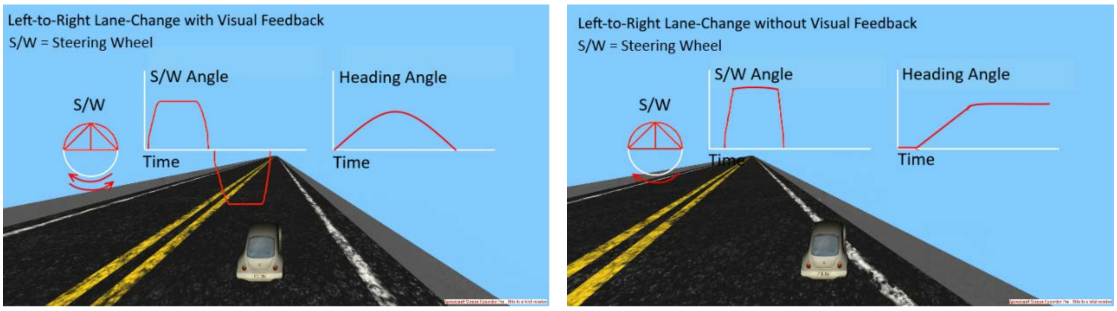

Figure 3 demonstrates a typical lane change maneouver with visual feedback (Left Figure) and a typical "lane change" maneouver without visual feedback (Right Figure). What is missing in the wrong "lane change" manoeuvre is the final steering movement. A proper lane change consists of a roughly sinusoid (bi-phasic) steering movement.

Although current evidence questions whether drivers are able to complete a lane change with no visual feedback, another everyday steering task, namely "curve negotiation", can be conducted in an open-loop manner. Godthelp (1986) and Wallis et al. (2007) have shown that visual occlusion does not affect drivers' ability to produce a cornering manoeuvre. Consistent with this finding, in a recent study on cyclists, Vansteenkiste, Van Hamme et al. (2014) found that during cycling along a circular path an anticipatory steering strategy is used at curve entrance while a compensatory closed-loop control is used during the cornering phase. The fact that a uni-phasic[4] manoeuvre can be conducted without feedback but a bi-phasic manoeuvre cannot, suggests that drivers require feedback to generate a second steering phase. However, recent work from Wallis' lab suggests that drivers are able to conduct a lane change without visual feedback, but only if they are asked to do an obstacle avoidance manoeuvre (Cloete and Wallis 2009). Since obstacle avoidance involves two lane changes, with the first one to avoid the obstacle and the last one to return to the original lane, it can be essentially treated as a tri-phasic manoeuvre (the last steering phase of the first lane change merges with the first steering phase of the last lane change). Taken together, they found that, without visual feedback, drivers conduct a bi-phasic manoeuvre if a tri-phasic manoeuvre is required and conduct a uni-phasic manoeuvre if a bi-phasic manoeuvre is required. Combining those interesting, systematic, erroneous

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[4] 'uni-phasic', 'bi-phasic', and the later 'tri-phasic' are defined based on movements of steering wheel. For example, Figure 3 – Left describes a 'bi-phasic' manoeuvre and Figure 3 – right illustrates a 'uni-phasic' manoeuvre. For an example of 'tri-phasic' manoeuvre please refer to Figure 1 in Cloete and Wallis (2009).

steering movements across lane change and obstacle avoidance with no visual feedback, Cloete and Wallis conclude that drivers may treat the steering wheel as a rate control device for lateral displacement, rather than the acceleration control device that it really is, the consequence being that drivers imagine that we glide left and right without changing heading rather than gently snaking down the roadway.

The original studies on lane changing were focused on the role of visual cues, Wallis, Chatziastros et al. (2007) then transferred the task to a simulator with motion platform to test whether the addition of vestibular cues evoked by car roll, tilt, and pitch, could trigger a complete lane change in no visual feedback condition. However, even after addition of these cues their participants still conducted the same systematic, erroneous steering movements. The results were largely in accord with those of Wilkie and Wann (2005) who concluded that vestibular cues provided by a motorized chair did not affect steering performance. Overall it seems that although drivers have the ability to conduct certain manoeuvres without visual feedback, they nonetheless have an incorrect internal representation of vehicle dynamics leading to systematic errors in tasks requiring multiphasic steering movements, even in the presence of a range of vestibular input.

Because neither a pure open-loop model nor a pure closed-loop model can fully capture the findings from Wallis' lab, it is reasonable to assume that drivers may steer vehicles in a way that an anticipatory strategy and feedback control are integrated, leading to a hybrid control model. Senders, Kristofferson et al. (1967) systematically investigated the correlation between visual occlusion and drivers' uncertainty about driving status. The results indicate that drivers reduce speed to compensate for short periods of occlusion, and, conversely, if a higher fixed speed is required, the driver need to look at the road more frequently. Through observations of driver's strategies and steering movements during visual occlusion, this study in fact implies a possible integration of feedback and feed-forward control. Later, Donges (1978) formally developed a "two-level" steering strategy, which employs both anticipatory control (open-loop) and feedback control (closed-loop). The "two-level" steering strategy suggests steering can be achieved by combining a guidance level involving preview of distant sections of the road in a feed-forward manner with a stabilization level consisting of deviation cancellation by monitoring near regions of road in a feedback manner. This proposal was later verified using a driving simulator by Land and Horwood (1995). Land et al. showed that by only presenting two 1-degree road segments consisting of one region close to vehicle and one region far from vehicle, drivers were able to steer accurately. Hence, they confirmed that the far region of the road provides information for the guidance level, while the near region provides information for the stabilization level. This “two-level” steering theory was further developed to the “two-point” steering strategy by Salvucci and Gray (2004). The “two-point” steering strategy suggests that drivers can use visual direction to a near point to maintain lane position and use visual direction to a far point to approach the upcoming road. Particularly, Salvucci and Gray claimed this “two-point” model is applicable to lane change manoeuvres. They showed that simulations based on the “two point” strategy produced lane change trajectories that were consistent with those generated by human drivers (Salvucci and Liu 2002, Salvucci and Gray 2004). The “two-point” steering strategy is essentially a closed-loop model, since it assumes drivers constantly measure visual direction to both near and far regions. That said, the authors explicitly mentioned that this model could incorporate an open-loop component to address the possible occurrence of an extended period of inattention during driving. Interestingly, a recent study shows evidence for an anticipatory level called “trajectory planning” on top of “guidance control” and “stability control” (Lehtonen, Lappi et al. 2014). Lehtonen et al. found that experienced drivers have shorter road-ahead (the segment for guidance level) fixation dwell times and longer look-ahead (the segment for trajectory planning) dwell times. They propose that a feed-forward component, namely “trajectory planning”, is integrated by experienced drivers to achieve smooth steering. It is now generally accepted that the “two-point” steering strategy is widely used by drivers during daily steering (Robertshaw and Wilkie 2008, Frissen and Mars 2014, Lehtonen, Lappi et al. 2014). Despite its popularity, a critical review from Cloete and Wallis (2011) reports that the results from one initial study (Land and Horwood 1995), in which the “two-steering” strategy is built, were heavily affect by the extremely low refresh rate employed, meaning that caution should be employed in interpreting this particular study.

In contrast to the two-point approach, Wann, Land, Swapp et al. proposed use of the “future path” (FP). FP proposes that drivers fixate the road ahead (1~2s ahead) and use streamers[5] towards that fixation to guide steering (Wann and Land 2000, Wann and Swapp 2000). Similar to the “two-point” strategy, FP emphasizes the contribution of visual direction to the fixation. This approach has more recently been characterised as “active gaze” (Wann and Wilkie 2004, Wilkie and Wann 2006, Wilkie, Wann et al. 2008, Wilkie, Kountouriotis et al. 2010). Further, FP and “two-point” strategies are not only capable of describing steering generally, but also a specific steering task such as corner negotiation.

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[5] Streamers refer to the integrated trajectories in the retinal flow during self-motion in an environment. Sometimes they are also called “lines”.

Corner negotiation, as mentioned above, can be treated as an open-loop steering task, with visual feedback acting in a compensatory manner for more precise control. Many studies have addressed which visual cues are used and how they are used to achieve precise control. Land and Lee (1994) proposed that during corner negotiation drivers use the tangent point to guide steering. The authors suggested that drivers can estimate the curvature of the corner directly through observation of the tangent point and steer to match that curvature. Alternatively, drivers can steer in a way that the visual direction with respect to tangent point remains constant during cornering (Land and Lee 1994, Wann and Land 2000). In contrast, Robertshaw, Wilkie et al. have suggested that drivers “look where they want to go” (future path) to negotiate a corner (Robertshaw and Wilkie 2008). They found that, if steering with free gaze, drivers direct their gaze towards the road ahead rather than the tangent point. Currently, there is some degree of disagreement on this topic. Some studies favour the future path strategy (Robertshaw and Wilkie 2008, Lappi, Lehtonen et al. 2013), whereas others prefer the tangent point solution (Kandil, Rotter et al. 2009, Authie and Mestre 2012). From a perspective of optic flow, Authie and Mestre (2012) suggest that the tangent point represents a local minimum of flow speed which, in turn, corresponds to minimum discrimination threshold in distinguishing curvature. Interestingly, recent studies have found that future path and tangent point are compatible with each other. It has been suggested that drivers may use future path and tangent point at different steering stages, for example, tangent point could be used to enter a corner whereas future path could be employed in later cornering phase (Lappi 2014). On-road experimental data also suggest that there is no evidence showing those two strategies are mutually exclusive, it is likely that drivers use multiple strategies in different situations during corner negotiation (Vansteenkiste, Van Hamme et al. 2014, Itkonen, Pekkanen et al. 2015).

The discovery of vestibular contributions in self-locomotion

While it is not surprising that visual cues play an essential role in self-locomotion, the fact that body rotation does not appear to affect vehicle steering behaviour is, perhaps, somewhat surprising. Many recent studies have described how the brain integrates visual and vestibular cues in the control of locomotion, at least during walking. The vestibular system contain organs for sensing both linear acceleration and rotation, for a review see (Angelaki and Cullen 2008). Telford, Howard et al. (1995) and Ohmi (1996), to our best knowledge, were among the first to conduct a formal heading perception task to systematically investigate the role of vestibular cues in self-locomotion. In their studies, both passive motion with linear acceleration on a track and active walking were tested. Although vestibular cues were presented during self-motion, Telford, Howard et al. (1995) showed that heading perception performance (threshold at 75% correct) in vestibular alone condition was at an order of ~10^o, well above that achieved when visual feedback was supplied (at an order of ~5^o). As a consequence, they concluded that vestibular cues alone are insufficient to guide self-locomotion, although they conceded that they may still be useful, especially when visual feedback is degraded. On the other hand, Ohmi (1996) found that in situations where visual cues and vestibular cues were in conflict participants relied more on vestibular cues, implying that the brain puts not inconsiderable emphasis on vestibular systems even when it is a relatively noisy source of information. Harris, Jenkin et al. (2000) and Bertin and Berthoz (2004) found that the presentation of vestibular cues significantly influenced perceived travel distances and trajectories, indirectly showing the potential contribution of the vestibular system in the regulation of self-locomotion. Later, Gu, DeAngelis et al. (2007) and Gu, Angelaki et al. (2008) showed for the first time that vestibular systems may participate in precise heading control tasks, which until that time had traditionally been thought to be dominated by our visual system. In their studies, they trained monkeys to conduct a heading discrimination task. They found that in the presence of vestibular cues, provided by passive motion at a peak acceleration around 0.1g, the trained monkeys achieved a discrimination threshold at an order of ~1^o, comparable to the best performance human observers can achieve. The results strongly suggest that vestibular cues do play an important role in self-locomotion. Many follow-up studies have since been working on building a model that integrates both visual feedback and vestibular cues. Fetsch, Turner et al. (2009), by manipulating the reliability of visual and vestibular cues, showed that primates can re-weight each cue dynamically on a trial-by-trial basis, consistent with a Bayesian assumption that the most reliable cue receive more weight. Recent studies generally agree with this finding (Butler, Smith et al. 2010, Campos, Byrne et al. 2010, Fetsch, Pouget et al. 2012, Saunders 2014, Butler, Campos et al. 2015), except that de Winkel, Weesie et al. (2010) found a mismatch between statistically optimal integration (i.e. Maximum Likelihood Integration) and the actual results in their experimental set-up. Interestingly, consistent with earlier studies (Telford, Howard et al. 1995, Ohmi 1996), most of the literatures has found that the brain appears to overweight vestibular cues relative to an ideal optimal integration model. That said, Saunders (2014) found the effect of overestimation on vestibular cues disappeared in his indoor active walking study, suggesting more investigations are needed to understand the integration of vestibular cues and visual feedback. In summary, it is now generally accepted that vestibular cues contribute to every walking (and potentially other self-locomotion tasks), and that they are in fact afforded more importance that might appear statistically optimal. Together, those findings challenge the common assumption that visual feedback dominates the regulation of self-locomotion and urge further investigations into the role of vestibular cues in general locomotion activities.

Issues that have not been previously addressed

As described above, it has been suggested that drivers possess an internal model of vehicle dynamics which is, on a fundamental level, wrong. The concept of an internal model has been proposed for a long time, especially in motor control studies (for a review see (Kawato 1999)). Evidence for an internal model comes from arm reaching studies, which show that humans can adapt to various visuomotor rotations, even though different external dynamics are imposed (for a review see Learning section of (Franklin and Wolpert 2011)). During such experiments, participants are typically required to move within an artificially generated force field with unfamiliar dynamics, a task they appear able to master even when the nature of this field remains obscure to them. Interestingly, one can relate this to vehicle's steering wheel, as steering wheel is another control device that can be operated even though its exact implementation may seem unclear to drivers. Nonetheless, during repeated trials humans can establish an inverse model for a desired trajectory in force field, but drivers still have a wrong representation of a desired steering manoeuvre despite some steering tasks are carried out frequently at a daily basis (e.g. lane change). The wrong representation internalized by driver may be due to the fact that drivers often perceive a vehicle's lateral position visually, rather than observing how he/she operates the steering wheel to approach a desired manoeuvre. Hence, during lane changing a driver perceives the change of the vehicle's lateral position, but is not aware of how exactly he/she operates the steering wheel during the manoeuvre. As a consequence, a common "naive physics" effect is grasped by drivers in a way that they believe through rotations of steering wheel the vehicle's lateral position can be altered directly without changes to the vehicle's heading. To date previous studies have only tested lane change on a straight road. Due to the forces acting on the steered wheels, steering-wheels have a natural tendency to re-centre themselves, allowing the driver to release the wheel when wishing to travel in a straight line. Consequently, a lane change manoeuvre on straight roads can be further divided into many small steps, e.g. steering, release, steering, release. Those many steps may prevent drivers from recalling a continuous, smooth steering movement during performance of a lane change. One solution to this issue is to design a circular road, on which a non-zero steering wheel angle is required at all times, without the possibility to passively release the steering wheel at any stage.

Another issue relates to the visual cues required for steering. Although an internal model is likely to guide steering with limited visual feedback, visual cues are still of crucial importance for a safe, precise control of steering. As described above, various visual cues and steering strategies have been extensively introduced. Given the importance of visual feedback, it is of interest to decide which visual cues are sufficient for daily steering tasks such as those typified by a lane change. Since optic flow is shown to be sufficient for a wide range of locomotion tasks, it provides a good starting point to investigate whether typical, dense flow fields are able to support a bi-phasic lane change. One might wonder if such an investigation is necessary since previous studies have thoroughly addressed the topic on steering in flow fields. It is important to notice that most previous steering studies involve an explicitly visible target, making an extra-flow cue, namely the “visual direction”, available. In this case, it would be difficult to separate the contribution from optic flow and visual direction in steering. As such, a novel method excluding any steering target would be more appropriate to address this issue.

Lastly, most real-world vehicle studies, if not all, focus on how different visible features influence steering (Kandil, Rotter et al. 2009, Lappi, Lehtonen et al. 2013, Lehtonen, Lappi et al. 2014, Vansteenkiste, Van Hamme et al. 2014, Itkonen, Pekkanen et al. 2015). These studies help address issues related to many steering models, as introduced above, but they were not able to investigate how non-visual cues may participate in steering. Currently, there is an increasing trend to further explore the role of vestibular systems in various locomotion tasks. During steering, vestibular cues are frequently presented and, most likely, are well above the noticeable level. So, do vestibular cues alone support everyday steering tasks, such as lane change? In the past, attempts were made to add vestibular cues by using motion platform in steering studies (Wilkie and Wann 2005, Wallis, Chatziastros et al. 2007). However, it is difficult to expect motion platforms to fully simulate the vestibular experience provided by a real vehicle in the real world. For example, the linear acceleration at an everyday driving speed of 50 km/h, the combination of translational movements and rotational movements while turning a vehicle, etc. Perhaps, the types of vestibular stimulation (rotational motion) tested by Wilkie and Wann (2005) and Wallis, Chatziastros et al. (2007) do not contribute much to driving, but there may be other inertial cues which do. Certainly, recent studies advocating the contribution of vestibular cues to locomotion during walking activities suggest that they might. In short, a real-word study using a real vehicle should allow us to investigate the role of full, natural vestibular (including otolithic) and somatosensory (e.g. protracted pressure exerted by the car seat during heading changes) feedback in steering.

An overview of studies in this thesis

To address the issues described above, three studies consisting of six experiments have been conducted using a diverse range of equipment.

In study 1 an experiment in lane-change on a circular road (Exp. 1) and an experiment in lane-keeping on a curved road with varying curvatures (Exp. 2) were conducted. In Exp.1, we investigated whether the classic lane change error appears on a circular road. Unlike the straight roads in all previous lane-change experiments, circular roads require participants to maintain a non-zero steering wheel angle most, if not all, of the time. The use of a circular road helps eliminate the tendency of a steering-wheel to re-centre itself, helping to test the generality of the earlier studies. In Exp.2 (pilot experiment), we compared participants' performance between steering a vehicle with a normal acceleration device and steering a vehicle with a rate control device (which may be drivers' "internal model" of vehicle dynamics). If drivers indeed internally treat the steering wheel as a rate control device, one can expect them to demonstrate reasonable performance in controlling heading in a car fitted with a rate-control device. This study was conducted in a fixed-base simulator. As a consequence, the results should be regarded as valid only in this "cue-conflict" situation. In other words, in this study we test drivers' "internal model" in the absence of vestibular cues (the standard condition in many steering studies).

In Study 2 Exp.1, a pilot experiment was carried out to investigate steering performance in steering towards a series of gates across different optic flow environments. In this experiment, we investigated the pattern of steering movements in each optic flow environment. Gates instead of a single target were used in Exp. 1. Different from traditionally used single target, gates restrict the range of heading angles a vehicle can adopt to pass through. In Study 2 Exp. 2 we conducted a lane change experiment in optic flow. Traditionally, it is believed that with dense optic flow and accurate heading perception an effective control of steering can be expected. In our experiment, we aimed to test whether accurate heading perception and dense optic flow necessarily leads to good performance in a lane change.

In Study 3, we conducted a pilot experiment using the latest head-mounted VR technology (an Oculus Rift DK2). Participants were required to conduct a forward lane change, a reverse lane change, and reverse parking (or parallel parking). Since reverse parking is essentially a bi-phasic manoeuvre (just like a lane change), it is of an interest to investigate whether the same, classic heading error appears during reverse parking.

In Study 4, we replicated the classic lane-change experiment on a real, instrumented vehicle. Although it has previously been shown that drivers still cannot perform a lane change with no visual feedback even when placed on a 6dof motion platform, no experiment to date has tested lane change with inertial feedback. A real vehicle provides natural inertial feedback and no conflict in the array of multi-sensory cues (e.g. on most simulators visual cues suggest movement but inertial cues suggest the opposite).

Finally, we should mention that the term ‘pilot’ used here and elsewhere in this thesis refers to early-stage experiments that were primarily used to validate some of our ideas and methodology. Pilot experiments usually did not involve as many participants as formal experiments did. Pilot experiments play an important role in the authors PhD studies, since many ideas, test methods, procedures, and simulator programs were deprived from certain early-stage pilot experiments. In this thesis, we report some pilot work (Study 1 Expt. 2, Study 2 Expt. 1, and Study 3) that we believe are representative to clearly demonstrate how we develop multiple research methods to address different research topics.

The driving simulator software developed by the author

The studies described in this thesis rely on access to a large projection system, an instrumented real vehicle and numerous simulated environments. An important part of the author’s PhD study has been to construct these test environments with the help of his PhD supervisor. The software was mainly written in C++ and consists of tens of thousands of lines of code. It integrates a wide range of specialist C++ libraries including OpenSceneGraph, SISL, Boost, OsgAudio, Oculus Rift SDK, OculusViewer, etc. It also makes use of NURBS (Non-Uniform-Rational-Basic-Splines) to generate roads. This method allows the experimenter to generate a road with any wanted shape and with any wanted curvature at any given position. Furthermore, the study incorporated the use of the Oculus Rift DK2 which was successfully used to do experiments with a HMD.

Since this program may be potentially useful to labs wishing to conduct similar experiments, the author made the program fully open source on Github. The source code can be obtained through the following link: https://github.com/xinbada007

Chapter Two - Study 1: A Test of Drivers' Internal Model of Steering

Experiment 1 Lane Change on A Circular Road

Introduction

It is still a matter of considerable debate as to which cues humans use to plan and control direction of travel in a motor vehicle. One class of manoeuvre which has received considerable attention over the last thirty years is based around lane changing and/or lane correction. The manoeuvre represents a self-contained control task requiring a biphasic steering movement to complete. In a series of studies Wallis and his colleges reported that classical steering models based on either open-loop (no feedback) or closed-loop (feedback) control fail to capture the results of the lane-changing experiments conducted using various driving simulators (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009). The authors reported that drivers make systematic errors during lane-change without any visual cue (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007). Interestingly, drivers are able to carry out the lane-change nearly perfectly with very limited visual feedback, lasting no more than 100ms, if it is presented during a critical time windows (Wallis, Chatziastros et al. 2007). These results suggest that lane-change cannot be simply attributed to either an open-loop or closed-loop model.

One concern is that previous studies conducted in Wallis' lab used straight roads only. The possibility arises that the tendency of a steering wheel to re-centre itself may impact the drivers' behaviour and render the result only true in the special case that passive release of the wheel results in the vehicle following the form of the road (straight). In this case, the participants' real intention might have been obscured by the characteristics of steering in a motor vehicle. For instance, participants might be misled by the concept that "release of the steering wheel makes the car goes straight". In fact, a car indeed stops turning after release of the steering wheel but the car's heading is not necessary aligned with the road. To examine whether drivers do make systematic errors during lane-change or they are just confused by this trait of steering wheels, we conducted an experiment on a circular road. Unlike straight roads, circular roads require a non-zero steering wheel angle at all times and hence the driver has to actively select a steering wheel response at all times. At no time point, may the driver passively release the steering wheel. Drivers in this experiment would be aware that they have to return to the non-zero steering wheel angle at the end of lane-changing manoeuvre instead of simply releasing the steering wheel and "going straight".

This experiment, as a result, provides an opportunity to examine drivers' behaviour during lane-changing without being affected by the potential influence from a self-centring steering wheel.

We used a fixed-base driving simulator consisting of a monitor and a force-feedback steering wheel. All experimental settings were similar to previous lane-changing experiments done in Wallis' lab except that the test road was circular. We would expect different results to emerge if the re-centring of steering wheel was the cause of the errors previously reported. However, if participants again demonstrate a similar pattern of errors then such errors are likely driven by a fundamental misconception of the impact of a steering wheel on the vehicle's heading, in other words, naïve physics as Wallis and his colleges suggested (Cloete and Wallis 2009).

Method

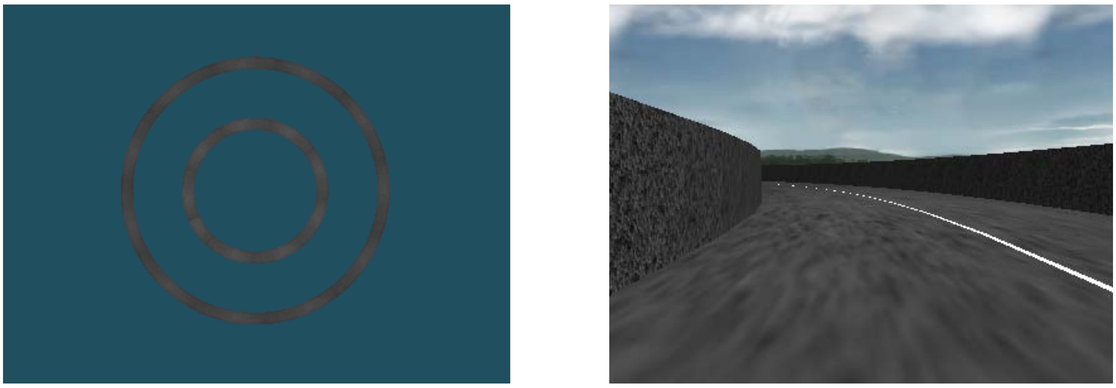

Figure 1. The virtual environment of this driving simulation. Left – aerial view, showing the roads of different radius (105m vs. 55m). Right – typical scene viewed from the vehicle driver's seat (a two-lane road).

Experiments were carried out on a circular road with two lanes. A set of counter-balanced experiments were designed according to different conditions, such as the radius of the circular road (105m vs. 55m), the starting lane (inner lane vs. outside lane), and the direction in which the vehicle travelled (counter clockwise vs. clockwise). The combinations of all these conditions were as follows:

Table 1 shows combinations of all conditions in this experiment

Radius	105m				55m			
Starting Lane	Inner Lane		Outside Lane		Inner Lane		Outside Lane	
Direction	Counter-	Clock-	Counter-	Clock-	Counter-	Clock-	Counter-	Clock-

There were in total 8 (conditions, as listed in Table 1) × 7 (repeats) = 56 trials. All subjects were required to complete two lane-changing tasks with and then without visual feedback in each trial. The lane-changing task with vision was to test whether subjects could change lane at all, and also provide an opportunity to familiarize them with the driving simulation. The simulation was developed on an SGI ONYX3200 computer using custom software based on OpenGL and SGI Performer libraries. A typical scene in this simulation is illustrated in Figure 1. The scene was rendered at a smooth frame rate of 72Hz. A typical 19-inch CRT monitor was used to display the scene. The resolution of the monitor was 1600 × 1200, the field of view was 57^o (horizontal) × 45^o (vertical). Participants sit in front of the monitor (about 60cm away from the screen) and used a Logitech MOMO force-feedback steering wheel to control the vehicle. The lag induced by this system has been estimated in the past (Cloete & Wallis, 2011) and with the improved linkage of steering wheel direct to the graphic PC via high-speed USB, the lag is currently dominated by the refresh rate of the system. Hence it varies from a few ms up to 14ms (corresponding to 72Hz refresh). During experiment, the simulated vehicle ran at a constant speed at 50 km/h. The procedure of each trail was described as follows:

1. Trial starts with full visual feedback.
2. Subject steers along the circular road.
3. Around 10 seconds' elapse and then a red bar is displayed on the screen as a trigger to ask subjects to change lane.
4. Around 10 seconds after Step 3, the screen is turned to black with a red bar on top of the screen as a trigger to ask subjects to change lane back into the lane they just came from.
5. Around 10 seconds after Step 4. The current trial ends without letting subjects know their performance for lane changing without visual feedback, and a new trial with a different condition begins from Step 1.

All these steps were preprogrammed in the simulator and executed automatically. The conditions listed in Table 1 were selected in a pseudo-random way for a given trial so that subjects could not predict what was coming next. In the full visual feedback condition, 10 seconds were given to participants to complete a lane-change. In the no visual feedback condition, 7 seconds were given to participants to complete a lane-change. A slightly longer duration was given in full cue condition because:

a) In the full cue condition, participants were asked to maintain the vehicle on road at all times. The slightly longer duration ensured that all participants had more than enough time to complete the lane-change and stabilize the vehicle afterwards.

b) The lane-change in the no cue condition always came after the lane-change in full cue condition. To avoid any carryover effect from the full cue condition, participants needed to stabilize the vehicle in the destination lane.

c) The slightly longer duration in the full cue condition also helped participants familiarize themselves before being exposed to the unusual no cue condition.

Participants

A total of 14 participants with current Australian driving license were tested although two were excluded from the analysis because they were unable to complete the task in the allotted 45 minutes. All participants had normal or corrected to normal vision. Before running the actual experiment, participants had the opportunity to practise driving the simulator until they fully understood the task and were comfortable with the virtual environment and steering wheel. All participants had at least three years' driving experience prior to this experiment.

Analysis

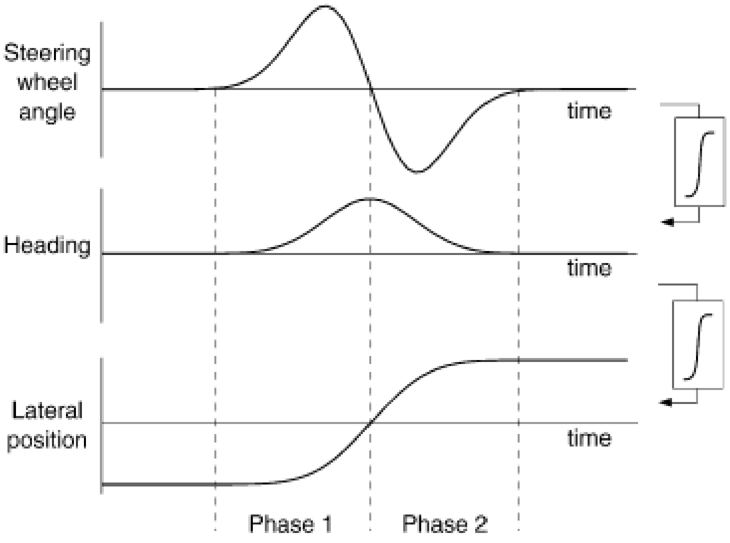

Figure 2. Lane-change task is characterized by a pair of steering movements: Phase 1 and Phase 2. In the case of lane change, the first phase involves changing the vehicle's heading, so as to cross

into the adjoining lane. The second phase involves an equal and opposite heading change required to straighten the vehicle.

Figure 2 shows the typical change of steering wheel angle against time, heading angle against time, and vehicle's lateral position against time during a lane-change. Drivers can only input steering wheel angle by controlling the steering wheel, but such input is translated into the vehicle's heading (which is the time-integration of steering wheel angles) and vehicle's lateral position (which is the time-integration of heading angles) through vehicle dynamics. The steering wheel profile shown in Figure 2 can be characterize as a sinusoidal function which can be conveniently divided into two phases --- the first half is the first phase and the second half is the second phase or return phase as it returns the vehicle's heading from peak to zero (straight relative to road). Obviously, no matter how much the driver deviated the vehicle's heading during the first phase, such deviation must be fully compensated by turning the steering wheel in the opposite direction in the second, return phase. Together, first phase and second phase compose a bi-phasic manoeuvre. After a bi-phasic lane-changing manoeuvre the vehicle's heading should be roughly zero relative to the direction of road, or a collision with the road edge is inevitable. Practically, small deviations from road (i.e. within 1~2 degree) after lane-change are probably allowed and unavoidable even visual feedback is presented, due to humans' limited precision on heading perception. Nonetheless, large deviations are hazardous and may not be able to corrected in time. For instance, a 5-degree deviation in a typical two-lane road would cause a vehicle running at 60 km/h to drive into the opposite lane within just a few seconds (depending on road width and the vehicle's position in lane). Given the risk, during the second phase drivers should align the vehicle's heading with the direction of the road as accurately as possible. As a result, the angular difference between the vehicle's heading and direction of the road can be used to measure the completeness of the lane-change manoeuvre effectively. If the angular difference is approximately zero, then the lane-change is successful. Conversely, if the angular difference is too large then the lane-change is performed incorrectly. In this experiment, the angular difference was renamed Heading Error. Due to the fact that Heading Error has two directions (left/right), we analysed both signed Heading Error and unsigned Heading Error (i.e. collapsed over two lane-changing directions).

Results

First, participants' Heading Errors for the full cue condition were analysed. On average, the unsigned Heading Error was 1.04 (M) ± 0.08 (SE) degrees. A one-sample t-test was conducted on unsigned Heading Error over participants, revealing that the unsigned Heading Errors were significantly larger than 0 ($t(11) = 13.46$, $p < 0.001$). The results suggest that participants did not fully align the vehicle's heading with the direction of road during the return phase. Since the drivers were able to continue driving successfully along the road, a deviation of around 1 degree can be regarded as normal and acceptable (Cutting 1986). Further, to find out whether participants had a similar Heading Error during normal curve negotiation, we also analysed the Heading Error at 4s before lane-change. The unsigned Heading Error at 4s before lane-change over participants was 1.09 (M) ± 0.07 (SE). A paired t-test was conducted on unsigned Heading Error after lane change (HE_{lc}) and unsigned Heading Error 4s before lane change (HE_{before}), showing there was no significant difference between those two variables, $t(11) = -0.623$, $p = 0.546$. This indicates that during normal curve negotiation, participants still showed a similar Heading Error. Therefore, the small deviation after lane-change with visual feedback is acceptable and unavoidable. As to the signed Heading Errors, the Heading Error for right lane-change with full cue (HE_{LR}) was 0.047 (M) ± 0.104 (SE) and the Heading Error for left lane-change with full cue (HE_{RL}) was 0.033 (M) ± 0.072 (SE). A one-sample t-test revealed that both HE_{LR} and HE_{RL} were not significantly different from zero ($t(11) = 0.451$, $p = 0.661$; $t(11) = 0.464$, $p = 0.652$; respectively). Participants showed an overall ~1^o unsigned Heading Error but an overall ~0^o signed Heading Error for both lane-change directions. This indicates that participants' signed Heading Error cancelled out each other. This was probably because participants did not have any tendency to oversteer to the left or right during lane-change in the full visual feedback condition. We further conducted a paired t-test on HE_{LR} vs. HE_{RL}. T-test showed there was no significant difference between the two, $t(11) = 0.108$, $p = 0.916$. The results confirm that participants showed no difference between right lane-change and left lane-change. Figure 3 shows lane-changing data of 12 participants from a single trial in the full-feedback cue condition. As shown in Figure 3, participants showed an offset (steering wheel angle > 0) at the beginning of the lane-change. Such an offset indicates participants were holding a non-zero steering wheel angle to negotiate the circular road. Interestingly, participants showed different offsets, indicating that, as predicated, participants could not precisely estimate the curvature. Figure 3 also shows that despite some differences in conducting the lane-change, all participants basically carried out biphasic-like steering movements with minor adjustments (see Figure 3, Left). Participants' actual lane-changing trajectories also tightly matched the expected trajectories (see Figure 3, Right). Expected lane-changing trajectory was simply a curved line along this circular road. Please be aware that the term "expected trajectory" was an abstract concept used for analysis. During experiment, only the lane-line that divided the circular road to left and right lane was visible to participants (see Figure 1, Right). Image during driving in the real word, the driver is supposed to keep his / her lane position, which consists of an “expected trajectory” over times, although there are no visible lines guiding every car at different lane positions. The small gap between the actual trajectories and the expected ones was caused by the lateral movement during the lane-change, i.e. a left change in this case (the red line is to the left of the blue line).

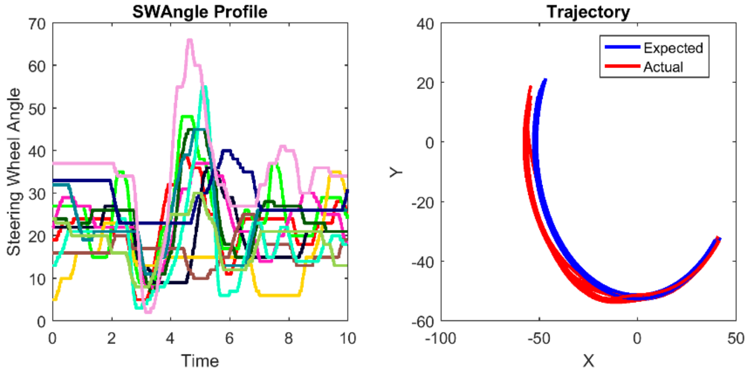

Figure 3 (left lane-change in full cue condition) illustrates trajectories (Right) and steering wheel profiles (Left) during lane changes with visual feedback across twelve subjects from a single trial under a single combination of conditions (small radius, clockwise, right-to-left lane change).

Second, participants’ Heading Errors in the no cue condition were analysed. The Heading Error for no cue condition over participants was 41.161 (M) ± 4.778 (SE). A t-test on unsigned Heading Error over participants indicated that the unsigned Heading Error was significantly larger than 0 (t(11) = 8.615, p < 0.001). Clearly, the large Heading Error shows that participants could not complete a lane change correctly without visual feedback. A further analysis on signed Heading Error was again conducted on right lane-change (HE_{NLR}) and left lane-change (HE_{NRL}). HE_{NLR} was -31.823 (M) ± 5.200 (SE) and HE_{NRL} was 34.566 (M) ± 5.754 (SE). Obviously, for right lane changes a large negative Heading Error (right to the road) was present, whereas for left lane-change a large positive Heading Error (left to the road) was present. A one-sample t-test showed that both HE_{NRL} and HE_{NRL} were significantly different from zero (t(11) = -6.008, p < 0.001; t(11) = -6.120, p < 0.001; respectively). The results strongly suggest that for both lane-change directions participants’ signed Heading Errors did not cancel each other out but biased toward the directions of lane-change. A paired t-test revealed that these two signed Heading Errors were significantly different from each other: t(11) = 6.624, p < 0.001. Taken together, the results indicate that the directions of Heading Error were tightly related to the directions of lane-change. A right lane-change resulted an oversteering to the right (negative Heading Error), while a left lane-change resulted an oversteering to the left (positive Heading Error). It is hard to imagine that this type of Heading Error was due to random factors, because otherwise one could expect participants to show negative Heading Errors and positive Heading Errors roughly equally for both lane-change directions.

Taken together, in the no cue condition the relation between Heading Error direction and lane-change direction (i.e. Heading Errors biased toward the direction of lane-change) suggests that participants did not conduct a return phase. As shown in Figure 4 (Left), participants only carried out the first phase of the lane-change manoeuvreer compared to Figure 3 (Left), leaving the second phase largely incomplete. Figure 4 (Right) confirms that participants always went off the road toward a specific direction. In this case, where participants were asked to carry out a right lane change, they always went off the road toward the right. It is worth mentioning that a random error in this case should have caused participants to go off the road toward the left and right in roughly equal times.

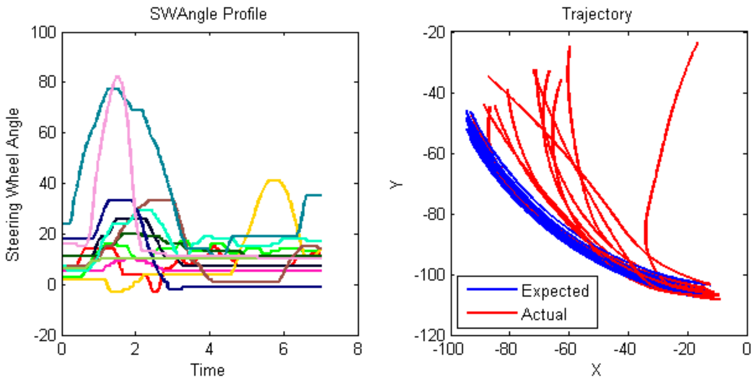

Figure 4 (right lane-change in no cue condition). *Left: changes of steering wheel angle through the lane-changing manoeuvre without visual feedback across twelve subjects from a single trial under a single combination of conditions (large radius, clockwise, left-to-right lane change). Right: expected lane-change trajectories and actual lane-change trajectories in this condition.*

Discussion

In 1985, a lane-change study conducted on both a simulator and an instrumented car showed that within 1s visual occlusion in simulator and 3s visual occlusion in real car, participants' performance was comparable with normal continuous visual feedback (Godthelp 1985). In a follow-up study in 2000, Hildreth et al. (Hildreth, Beusmans et al. 2000) investigated visual occlusion in a lane-correction manoeuvre. Their results show that with 1.5s to 2s visual occlusion the lane-change was performed as well as if participants had had full visual feedback. Both Godthelp and Hildreth et al. suggested an open-loop model for steering control for a short period of absence of visual feedback. It appeared that a lane-change manoeuvre can be regarded as an open-loop manoeuvre with visual feedback only needed for correcting minor, accumulating errors. Nonetheless, there were two problems in both studies. First, 3s visual occlusion might be too short to reveal participants' true lane-change behaviour. It is likely that within the first 2 to 3s, participants just completed the first phase, after which they received full continuous visual feedback. Participants then might use visual cues to conduct the rest of lane-change. If this was the case, instead of claiming the entire lane-change manoeuvre is open-loop, one can only conclude that first phase can be conducted with loop opened, since the rest was carried out with full visual feedback. Second, feedback of participants' final performance was always available because visual occlusion was only for the first 2 to 3s, which raised the possibility that participants might change their behaviour after knowing their lane-change results. In this case, even if participants mistakenly conducted the required lane-change task in the first few trials, they were able to correct such errors in the following repeated trials on the basis of prior experience. As a result, on average, participants could demonstrate an overall good lane-change performance. The effect of change of behaviour was illustrated in a study done by Wallis et al. (Wallis, Chatziastros et al. 2002), in which they showed that in the presence of performance feedback participants changed their behaviour trial after trial until almost perfect lane change was achieved. Of course, if participants changed their behaviour during the experiment, naïve behaviour would be lost due to the effects of averaging with non-naïve trials.

Wallis et al.'s, studies used a different experimental design, in which the visual occlusion covered the entire manoeuvre till the very end of each trial, ensuring participants had to complete lane change without visual feedback and were not aware of their own performance. This approach was used in the study described here, and we once again found evidence for systematic errors (Figure 4) during lane-change without visual feedback. The direction of Heading Errors in the no cue condition was always related to the direction of lane-change. As well as supporting Wallis et al.'s previous findings, this study generalized the conclusion by conducting the experiment on a circular road which eliminated the possibility that participants simply turned-and-released the steering wheel on a straight road. Taken together, we propose that without visual feedback drivers make systematic and repeatable errors during lane change.

So, what causes these systematic errors? Firstly, it was not because of the longer duration of visual occlusion suggested by Zhao et al. (Zhao and Warren 2015). The duration of visual occlusion needs to cover the entire lane-change period or it may not reflect participants' real intention. It is true that with longer visual occlusion any error would accumulate. Nonetheless, the systematic errors found here were clearly not some random errors being accumulated. As both the t-tests and the figures suggested, participants always went off the lane-change in the direction of the lane change. In the case of random errors, participants should have demonstrated no bias toward lane-change directions. So why do participants always miss the second phase in the absence of visual feedback? One explanation is that drivers may treat the steering wheel as a rate control device for lateral position, rather than as the acceleration device it really is (Figure 2 shows a typical acceleration system). Indeed, in 2009 Cloete et al. found that participants displayed a similar erroneous performance in steering movements typified by obstacle avoidance, consistent with the 'naïve physics' hypothesis (Cloete and Wallis 2009). In their experiment, they let participants carry out an obstacle avoidance, which essentially was equivalent to two lane changes – the first one to avoid the obstacle and the second one to steer back to the original lane. This sort of steering movements can be captured by a tri-phasic sinusoidal function (for detail see Figure 1 in Cloete and Wallis 2009). Surprisingly, instead of doing a required tri-phasic manoeuvre, they found participants conduct a bi-phasic manoeuvre, resulting a lane change. With visual feedback, any error caused by "naive physics" will be reflected by visual cues and drivers can adjust accordingly. Interestingly, it is also found that even brief visual feedback during a critical time window is sufficient for drivers to conduct a lane change. In 2007 Wallis et al. found that with as little as 100ms visual feedback occurred at the very end of first phase drivers are able to conduct a nearly perfect lane-change (Wallis, Chatziastros et al. 2007). This finding suggest that full visual feedback may not be necessary to correct errors caused by "naïve physics". This is consistent with drivers' daily experience --- they do not need to monitor heading continuously.

Conclusion

We conducted a lane-change experiment on a circular road with and without visual feedback. Participants showed systematic errors when they had to complete a lane change in the absence of visual feedback. The results are consistent with previous work (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007). Since the systematic errors were found on both straight and circular roads, we propose that the errors were not due to the vehicle wheels' self-centering, but due to the "naïve physics" internalized by drivers. Sufficient, but not full, visual feedback is needed to complete the manoeuvre.

Experiment 2 Curved Road Driving Test Under Two Vehicle Dynamics (A Pilot Experiment)

Introduction

In the light of the previous experiment, we suggest that drivers treat steering wheel as a rate control device for vehicle’s lateral position, which is similar to a four-wheel steering vehicle in which all four-wheels steer at the same angle relative to the long axis of the vehicle, which can be described as a “naïve physics” effect. As a result, drivers always miss the final steering phase in various tasks such as lane-change (bi-phasic manoeuvre) and obstacle avoidance (tri-phasic manoeuvre). Given the results, it is reasonable to ask whether drivers would notice any difference between these two vehicle dynamics if both are present. It would be interesting if drivers do feel they are controlling a rate control device during driving, since from a mathematical perspective those two vehicle dynamics are quite different.

Nonetheless, one concern might be that why drivers still control their vehicles effectively if they do misunderstand vehicle dynamics. One possible explanation is that the vehicle dynamics are apparent to the driver as long as it generates satisfying outputs. The driver’s task is not to explore the underlying mechanism, but to monitor whether the output matches their expectations. Some widely-accepted steering-control models describe how effective steering can be achieved by monitoring a few variables (Donges 1978, Land and Lee 1994, Land and Horwood 1995, Wilkie and Wann 2003, Salvucci and Gray 2004). The “two-point” steering strategy, for example, is a now popular model proposed by Salvucci and Gray (2004). The “two-point” model suggests that the control of steering can be described as maintaining constant visual direction to both near and far targets (that said, for a critical review see (Cloete and Wallis 2011)). Interestingly, however, Figure 1 shows that on a roughly straight road, “two-point” steering strategy can be used under either vehicle dynamics --- by switching both the near target and the far target to destination lane and then steering toward them, a lane change can be produced regardless of vehicle dynamics. From this perspective, drivers can indeed control steering effectively without fully understanding the underlying vehicle dynamics.

In this pilot experiment, we investigated whether drivers would show significant differences in performance in steering under different vehicle dynamics (i.e. rate control device vs. acceleration device). A task consisting of curve-negotiation and lane-keeping was used to measure participants' steering performance with both vehicle dynamics. The assumption is that if steering performance between two vehicle dynamics is comparable, then it would be natural for drivers to treat the steering wheel as a rate control device for vehicle's lateral position.

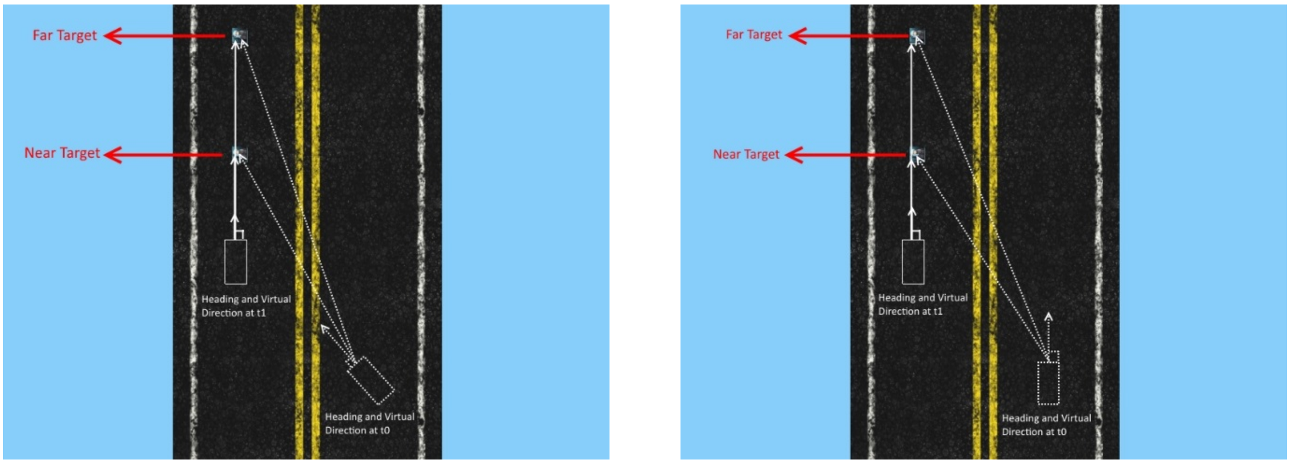

Figure 1 illustrates that the "two-point" strategy for both vehicle dynamics (Left: acceleration, Right: rate control). The desired visual direction (0^{o} *in this case) to both far and near targets is achieved by either changing vehicle's heading and lateral position (acceleration device) or lateral position only (rate control device).*

Method

In this experiment, we carefully designed a simulated vehicle that can switch its dynamic between a second-order (acceleration) and first-order (rate) control device for lateral position. Because a rate control device cannot change its heading, an algorithm was implemented (see Appendix) to allow the vehicle to drive itself and adjust its heading smoothly and automatically in such a way that the vehicle always faced in the direction of road, in a manner similar to the way that people drive real vehicles on real roads. In this condition, participants could only laterally shift the vehicle through steering wheel movements. In this case, the vehicle's "shifting speed" was set from 0 m/s to 21 m/s, depending on steering wheel angle. In the case of an acceleration device, the vehicle's rotation speed was set up to a maximum of 42.5 degree/s.

We let subjects drive the vehicle with the two types of dynamics over various combinations of speeds, road curvatures, and starting lane. The participants' task was to drive the vehicle while maintaining the vehicle's initial, starting lane position as precisely as possible. There were three blocks in this experiment, each of which had a fixed combination over speeds and road curvatures (Table 1). The order of blocks was counterbalanced between participants. In each block, there were 2 (starting positions: left/right lane) × 2 (vehicle dynamics) × 1 (repetition)= 4 trials. In total, there were 4 (trials) × 3 (blocks) = 12 trials. In each trial, participants drove the vehicle on a road at a constant speed. Each road had three sections, each of which had different upper limits of road curvatures (see each row in Table 1). For example, Row 1 in Table 1 shows that in block 1 participants drove the vehicle on a road at a speed of 50 km/h. In addition, Row 1 indicates that the road consisted of three sections with different curvatures. The curvatures listed in Table 1 were only upper limits, which means each section of road was not at a constant curvature (Figure 2). Each section had the same length requiring 60 seconds to drive through regardless of the speed, resulting in a total of 180 seconds to drive the whole road. The use of non-constant curvatures required participants to actively negotiate the roads, rather than to hold a non-zero steering wheel angle at all times. This presented a more natural, challenging task to participants since they had to adjust the steering wheel at all times to negotiate the roads while maintaining the vehicle's lane position. Please be aware that the "required lane position" was not a visible lane mark to participants, rather it was an abstract concept that participants should keep in mind. For example, when driving in the real world, there are supposed lane positions for cars but such positions are not explicitly marked on roads.

The roads were at width of 3.75 meters and generated using a set of Non-uniform-rational-basic-spline (Nurbs) control points. Nurbs is widely used in computer graphics to generate complicated and controllable curves. Many previous studies used analytic functions (i.e. circular functions or some combinations of sin/cos functions) to generate their curved roads, which differs from the clothoids used on real roads and it is quite limited in the form of curve it can produce. In contrast, a Nurbs is able to generate curves of any shape. Nurbs can also control local curvature at any given position. We used this method to generate pseudo-random curves as shown in Figure 2a. Figure 2b shows a typical scene in this simulation. The scene was rendered using a program developed by the author, as described in Chapter 1. A Panasonic RZ-470 projector running at 60Hz was used the display the scene. The screen provided a resolution at 1920 × 1080, and a field of view at 69^o (horizontal)× 42^o (vertical). Participants sit in front of the screen (about 2.5 meters away from the screen) and used a Logitech MOMO force-feedback steering wheel to control the vehicle.

Table 1 *illustrates all blocks divided by speed and road curvature.*

Block	Speed	Road Radius (Section 1)	Road Radius (Section 2)	Road Radius (Section 3)
1	50 km/h	40 m	32 m	25 m
2	75 km/h	75 m	65 m	55 m
3	100 km/h	125 m	115 m	105 m

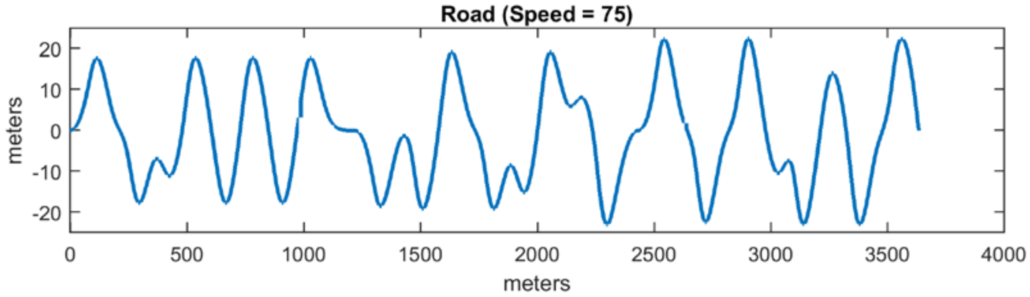

Figure 2a illustrates the road used for block 2 (speed = 75km/h, equivalent to 20.83 m/s). This road consisted of three sections, each of which was identical in length, but different in curvature. The total length of this road is 3750m requiring 180 seconds to drive along (20.83 m/s × 180 seconds ≈ 3750m).

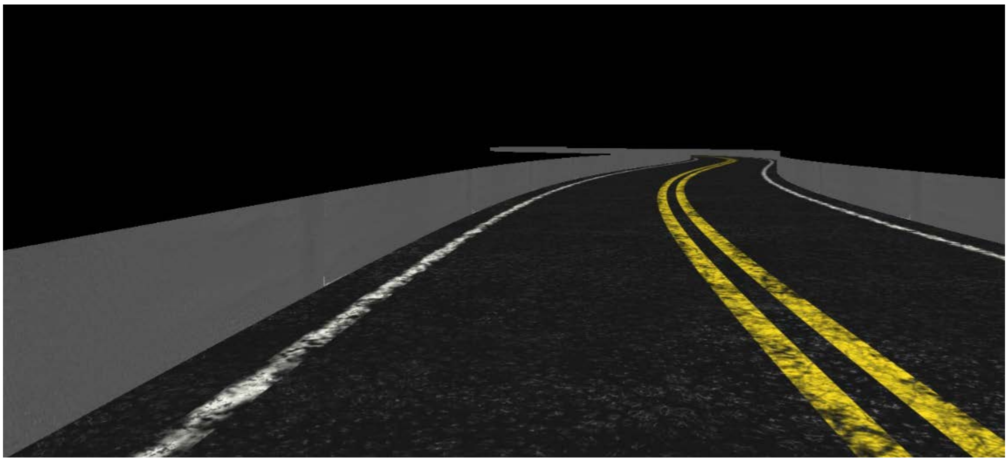

Figure 2b shows a typical scene in this experiment.

Participants

6 drivers (3 females + 3 males) aging from 18 to 30 participated in this experiment. All of them were naive to the purposes of the experiment and all had normal or corrected-to-normal vision. Participants had driving experience from 2 years to 10 years. Participants were instructed to drive along the road while maintaining lane position (centre of the starting lane) as precisely as possible. In order to prevent them from noticing the fact that the simulated vehicle can drive itself with the designed rate control dynamics, we instructed

them to actively control the steering wheel at all times. Before the experiment began, all participants were given an opportunity to practise. Only the normal, acceleration dynamics were used in the practice session.

Analysis

Lateral deviation (both signed and unsigned) from required lane position were analysed. Mean lateral deviation and RMS of lateral deviation were used as measurements to reflect steering performance. Since signed lateral deviation has two directions, we defined that positive = right and negative = left. In addition, a Fast Fourier Transform (FFT) was performed to analyse the frequency and energy of participants' steering movements. FFT would help reflect whether participants were struggling with the steering wheel under a particular vehicle dynamics, e.g. if the majority of energy consumed was in the higher frequencies, one could conclude that participants had to adjust the steering wheel frequently, implying an uncomfortable control. This is because participants' control of the steering wheel can be seen as a series of signals, which can be approximated by Fourier series. FFT gives the distribution of amplitudes across the spectrum of frequencies. If participants frequently rotated the steering wheel, then they would demonstrate noticeable amplitudes at higher frequencies. Energy is integration of FFT over frequencies and as a result it can reflect how participants controlled the steering wheel. "Energy" or "power" are terms used in this type of analysis.

Results

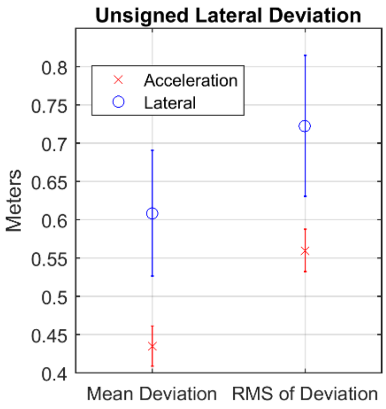

Figure 3 demonstrates mean unsigned lateral deviation and RMS across two vehicle dynamics. Error bars are SE.

First, the mean unsigned lateral deviation was analysed. The results show that the mean unsigned lateral deviation for both vehicle dynamics were very close (Figure 3). For the rate control dynamics, the mean deviation was 0.609 (M) ± 0.082 (SE); whereas for the acceleration dynamics, the mean deviation was 0.435 (M) ± 0.026 (SE). A paired t-test shows that there was no statistically significant difference between the two: t(5) = 2.199, p = 0.079. The results generally suggest that participants performed equally well under the two dynamics. The RMS of lateral deviations was also analysed over participants. RMS reflects precision of the control of steering. RMS was 0.723 (M) ± 0.092 (SE) for the rate control dynamics, and was 0.560 (M) ± 0.028 (SE) for the acceleration dynamics. A paired t-test suggested there was no statistically significant difference between the two RMS: t(5) = 1.599, p = 0.171. Again, the RMS results suggest that participants performed equally well with both vehicle dynamics. Nonetheless, one concern might be that with the rate control dynamics whether participants controlled the steering wheel or not. It is possible that the data for the rate control dynamics was essentially non-human data, if participants simply let the vehicle drive itself. Therefore, we also ran the experiment using the driverless algorithm. The mean unsigned lateral deviation for the algorithm was 1.049 (M) ± 0 (SE), and the RMS for that was 1.230 (M) ± 0 (SE). Both results were very different from that of human data. Obviously, participants must have steered the vehicle under rate control dynamics otherwise they would not have shown different results.

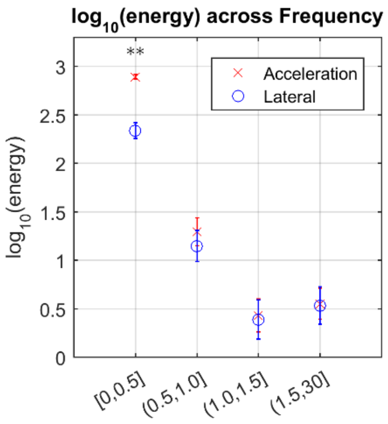

*Figure 4 demonstrates average FFT amplitudes across four frequency ranges under two vehicle dynamics. Error bars are SE. "**" indicates 0.01 level.*

To analyse the control of steering for both vehicle dynamics, a Fast Fourier Transform (FFT) analysis was performed. FFT shows the frequency and energy of the control of steering (Figure 4). More energy on higher frequencies suggest participants were likely struggling with the steering wheel while more energy on lower frequencies suggest participants were controlling the steering wheel smoothly and comfortably. In this experiment the simulator was running at the 60Hz, the resolution of FFT was then 0~30Hz. We further divided the frequencies into four groups (unit is Hz): [0,0.5], (0.5,1.0], (1.0,1.5], (1.5,30]. The energy over each group was analysed over participants. For the rate control dynamics, the energy (adjusted to $\log_{10}$) over [0, 0.5] was 2.341 (M) ± 0.082 (SE), over (0.5,1.0] was 1.148 (M) ± 0.161 (SE), over (1.0,1.5] was 0.388 (M) ± 0.202 (SE), and over (1.5,30] was 0.532 (M) ± 0.195 (SE). For the acceleration dynamics, the energy (adjusted to $\log_{10}$) over [0,0.5] was 2.895 (M) ± 0.022 (SE), over (0.5,1.0] was 1.294 (M) ± 0.143 (SE), over (1.0,1.5] was 0.430 (M) ± 0.169 (SE), and over (1.5,30] was 0.551 (M) ± 0.161 (SE). From simple calculations[6], energy over [0, 0.5] consisted of ~96% of the total energy regardless of vehicle dynamics. The results suggest that the control of steering was smooth and comfortable for both vehicle dynamics. A paired t-test was performed on energy over vehicle dynamics (i.e. energy for rate control

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[6] Note the results of log_{10}^{energy}. The actual energy can be obtained. Take the rate control device as an example, the energy on [0, 0.5] = $10^{2.341}$ = 219.28, the energy on (0.5, 1.0] = $10^{1.148}$ = 14.06, and so on. Therefore, it is easy to know that energy on [0, 0.5] dominates.

dynamic vs. energy for acceleration dynamics) for each group, revealing that for the energy over [0, 0.5] for rate control dynamics was significantly lower than that for acceleration dynamics, t(5) = -5.432, p = 0.003. No other statistical significance was found. This suggests that for the same main frequencies range [0, 0.5], participants spent more energy in steering the acceleration device. The reasons for this inequality in energy could be two-fold. First, for the rate control dynamics participants only needed to control the vehicle's lateral position, whereas for the acceleration dynamics participants needed to control both the vehicle's lateral position and its heading. Second, for the acceleration dynamics a bi-phasic steering movement was needed to adjust the vehicle's lateral position (i.e. making a lane change to reach required lane position), whereas for the rate control dynamics only a uni-phasic steering movement was needed.

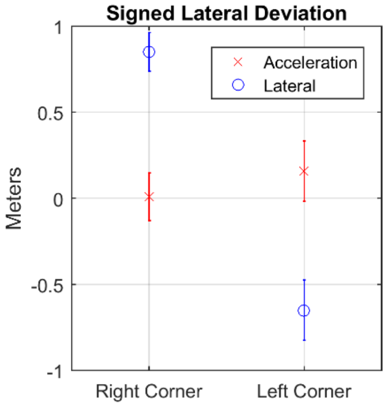

Figure 5 shows signed lateral deviation for leftward corners and rightward corners across two vehicle dynamics. Error bars are SE.

From the results above, it seems that participants felt comfortable in controlling a rate control device and they performed comparably well under either condition. One may also want to know how participants performed when they negotiated corners. One possibility is that, if participants did not realize they were controlling a rate control device whose heading was automatically changed by an algorithm, they might still try to "change" the vehicle's heading during cornering by rotating the steering wheel. To investigate this possibility, we analysed signed lateral deviations over leftward and rightward corners. For the rate control dynamics, if participants did rotate the steering wheel to negotiate corners, one could expect leftward (negative) deviations for leftward corners and rightward (positive) deviations for rightward corners. The analysis was done in a way that for each corner the point of highest curvature was first obtained and then signed lateral deviations was calculated from 60 data points consisting of from the position 0.5s before reaching the point to the position 0.5s after arriving the point. Figure 5 shows that for the rate control dynamics participants showed a positive (rightward) deviation (0.851 (M) ± 0.112 (SE)) for rightward corners and a negative (leftward) deviation (-0.650 (M) ± 0.175 (SE)) for leftward corners. A paired t-test shows that, as expected, for the rate control dynamics there was a significant difference on signed lateral deviation between rightward corners and leftward corners (Figure 5): t(5) = 5.335, p = 0.003. On the other hand, for the acceleration dynamics participants showed positive deviation (010 (M) ±

0.138 (SE)) for rightward corners and positive deviation (0.158 (M) ± 0.176 (SE)) for leftward corners. A paired t-test shows that for the acceleration dynamics there was no significant difference in signed lateral deviation between rightward corners and leftward corners, t(5) = -0.521, p =0.624. Figure 6 shows participants' trajectories when negotiating a leftward corner for both vehicle dynamics. The results suggest that even for the rate control dynamics, participants still drove the vehicle in a way that was only suitable for an acceleration device. Perhaps this suggests that participants did not distinguish the two vehicle dynamics used. This is consistent with the negative results orally reported by four out of six participants when they were asked to indicate any noticeable change on vehicle during the experiment. That said, we should mention that this subjective measurement may not fully reflect participants' real intention since they might misunderstand the question or the question was not precise enough. It remains possible that participants sometimes noticed the change on vehicle dynamics, but this did not appear to impact their steering behavior, as suggested by the data. Participants might intuitively believe they could change the vehicle's heading if necessary without knowing the underlying vehicle dynamics. Interestingly, this is consistent with previous finding, the "naïve physics", that participants believed they could "shift" the vehicle laterally without knowing the mechanism.

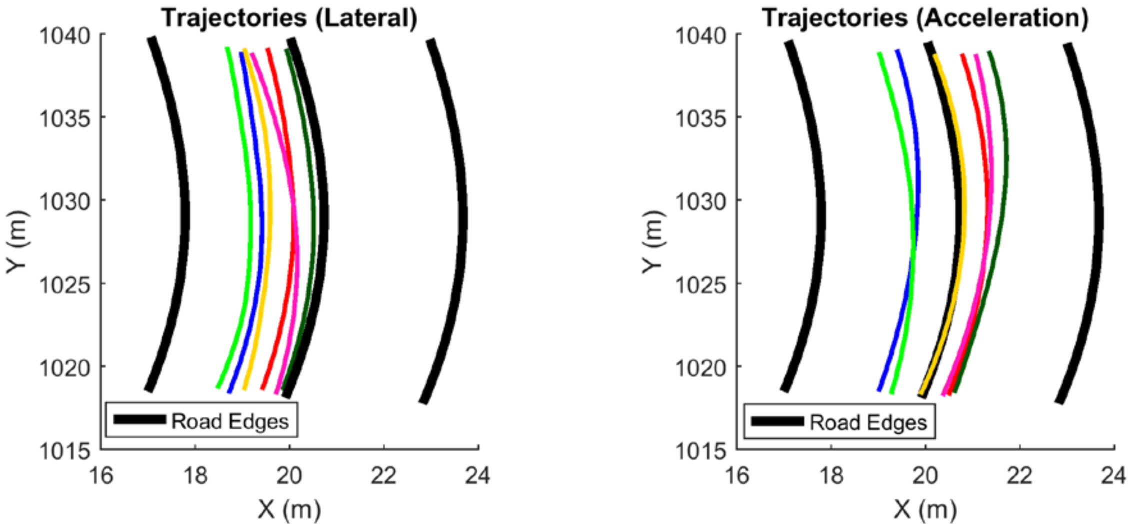

Figure 6 shows trajectories of participants negotiating a leftward corner with the acceleration dynamics (Right) and the rate control dynamics (Left). Colourful lines indicate participants' trajectories from 0.5s before arriving at the point of highest curvature to 0.5s after passing that point. Bold black lines indicate road edges. The required lane position is illustrated by the central bold black line. Note that the central bold black line was invisible to participants.

Discussion

In this study, we conducted an experiment to investigate whether participants could drive a vehicle fitted with a rate control device while maintaining good overall performance. Participants were instructed to maintain their initial lane positions at all times while driving through the roads. The results generally show that with the rate control dynamics, participants achieved a comparable performance (relative to the performance of the acceleration dynamic) in maintaining lane position. The FFT analysis indicates that participants were comfortable with a rate control device, as shown by the energy consumption within the range of low frequencies (Figure 4). We also discovered that participants spent significantly more energy in controlling the acceleration device. We believe this was because with the acceleration dynamics participants had to control both the vehicle’s heading and lateral position. Interestingly, participants seemed not to have discovered the “trick” of the rate control dynamics since they attempted to change the vehicle’s heading even when exposed to rate-control dynamics. Nonetheless, for the rate control dynamics the attempt of “changing heading” resulted in systematic signed lateral deviations (Figure 5 and Figure 6).

Taken together, it seems drivers can control vehicles without understanding underlying mechanisms. Perhaps drivers do not focus on mechanisms during driving. Reference objects such as lane lines and landmarks on roads provide drivers with a strong guide to steer by. People only need to monitor a few variables such as lane position and visual direction to landmarks to steer effectively. Such a process does not require any knowledge of vehicle dynamics as long as the vehicle responds to inputs in a reliable way. For example, after training, people can master the steering systems of various vehicles, tankers, airplanes, etc. As a result, it is not surprising that, without special training, drivers develop a wrong internal model during daily steering through their “naïve physics”. Previous work (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009, Xu, Wallis et al. 2014) shows that for a normal, acceleration device drivers keep making systematic errors during lane-change without visual feedback. This suggest that steering cannot be simply regarded as either an open-loop model or closed-loop model. Visual feedback is not only a source for correcting accumulated errors but also a source for correcting drivers’ internal models.

We should also mention that this experiment relied on the designed “driverless” algorithm. If this algorithm had steered the vehicle in an unusual way, then participants would have easily noticed this artifice and behaved differently. This algorithm is explained in detail in the Appendix section immediately following the Conclusions below.

Conclusion

We conducted an experiment to investigate one necessary condition of the “naïve physics” effect --- if drivers indeed treat an acceleration device as a rate control device, they should demonstrate reasonably good performance in controlling either device. Our results show that participants comfortably controlled both types of vehicle and achieved similar performance. We conclude that people drive vehicles without the understanding of the underlying mechanisms. As a result, sufficient visual feedback is needed to correct any error caused by drivers’ erroneous internal model.

Appendix The 'self-driving' Algorithm

One essential part of this experiment was to design a driverless algorithm to control the simulated vehicle automatically traveling along the roads as naturally as possible. For this purpose, we implemented an algorithm inspired by Salvucci et al.'s two-point steering model (Salvucci and Gray 2004), Wann et al.'s future path strategy (Wann and Land 2000, Wann and Swapp 2000, Wilkie and Wann 2006, Wilkie, Wann et al. 2008), and Frissen et al.'s most recent finding (Frissen and Mars 2014). In this algorithm, two points are chosen to calculate vehicle's heading error, which is then used to steer the vehicle. The two points consist of one near point and one far point, as proposed by Salvucci et al. In this algorithm, the near point is the vehicle's current position, indicating how much the vehicle deviated momentarily (HE_{Near}). Due to the fact that at high speed any deviation should be corrected in a relatively short time (otherwise a collision with road edge is expected), we also introduced speed as a scaled factor: HE_{Near} = Deviation × Speed. In order to prevent the algorithm being too sensitive to minor heading errors, we set a threshold of 1^o to trigger the algorithm. 1^o was chosen because previous work shows that 1^o~2^o is humans' upper limit to perceive heading changes (for a review, see (Lappe, Bremmer et al. 1999)). A far point is also chosen to calculate how much the vehicle should turn to reach its destination (HE_{Far}). In this algorithm, a valid far point has to satisfy the following two conditions: a). the deviation between the far point and the vehicle has to exceed 1^o; b). the far point has to be no more than 1s' away from the vehicle. The first condition is to ensure the vehicle is not too sensitive to minor heading errors. The second condition is to satisfy future path strategy proposed by Wann et al. that suggests humans usually look ahead 1~2s during self-locomotion. Heading Error of far point is also scaled: HE_{Far} = Deviation ÷ (Distance ÷ Speed) => HE_{Far} = Deviation ÷ Time. This is to reflect the fact that relatively small steering is needed if the vehicle has long enough time before reaching its destination. At last, the final Heading Error (HE_{Final}) used to control the vehicle is not an additive process of HE_{Near} and HE_{Far}, as suggested by Frissen et al. (Frissen and Mars 2014). In this algorithm, we set HE_{Final} = max (HE_{Near}, HE_{Far}), that is, HE_{Final} equals the bigger one between HE_{Near} and HE_{Far}. In case of HE_{Near} = HE_{Far}, this algorithm always set HE_{Final} = HE_{Near}.

After the experiment was done, we were able to compare steering behavior between human participants and the algorithm. The vehicle's wheel angle (i.e. wheel angle was associated to steering wheel angle) at every frame was used to do the comparison (Figure 1). Figure 1 shows that the algorithm responded to road curvatures slightly earlier than humans did. This phenomenon appeared in every trial throughout the experiment. The lead shown by the algorithm was likely due to the reaction time of humans, i.e. the time period from noticing any deviation to actually steer vehicle. Cross-correlation results show the mean lead for the algorithm (unit is second) was 0.620 (M) ± 0.172 (SD). Given the small lead and the high cross-correlation coefficient (0.913 (M) ± 0.034 (SD)), we conclude that the algorithm captures humans' steering behavior reasonably well. This is also confirmed by the high R-Square between humans' data and the algorithm's data (adjusted to its lead): 0.829 (M) ± 0.062 (SD). Taken together, the algorithm produces a natural steering behavior similar to human drivers.

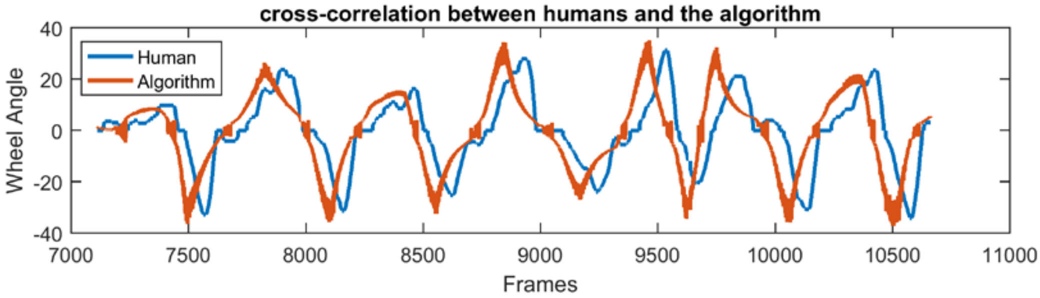

Figure 1 illustrates the wheel angle profiles for one participant and that for the algorithm for about 3750 frames.

Chapter Three - Study 2: A Test of Steering in Optic Flow

Experiment 1 Gate Crossing in Optic Flow (A Pilot Experiment)

Introduction

Since Gibson (Gibson 1950, Gibson 1958) first introduced the concept of optic flow, many follow-up studies have served to confirm that optic flow plays an important role in human locomotion (Warren and Hannon 1988, Warren and Hannon 1990, Hildreth 1992, Van den Berg 1993, Banks, Ehrlich et al. 1996, Ehrlich, Beck et al. 1998, Lappe, Bremmer et al. 1999, Warren, Kay et al. 2001, Wilkie and Wann 2002, Fajen and Warren 2003, Wilkie and Wann 2003, Li, Stone et al. 2011, Kountouriotis, Shire et al. 2013, Li and Niehorster 2014). It is currently generally believed that with sufficient optic flow and extra-retinal information (i.e. eye-movement signals), one can locate his/her heading to an accuracy of 1~2 degrees under a range of situations (Li and Warren 2000, Li and Warren 2002, Li and Warren 2004). That said, early discoveries were mainly found in a series of experiments that did not involve any heading control task but a forced-choice task. Participants in those early studies were usually only asked to judge heading passively, rather than to actively make use of heading. Consequently, one might ask the question whether excellent performance in passive heading judgements translate to good performance in real-time active heading control tasks. The good news is that recently there is an increasing trend to investigate optic flow (along with other cues such as visual direction) in active steering tasks.

In a series of steering-toward-a-goal experiments, Wann and Wilkie (Wilkie and Wann 2002, Wilkie and Wann 2003, Wann and Wilkie 2004) found that human observers do not rely solely on optic flow for locomotion. In their experiments, they asked participants to steer toward a goal over various combinations of extra-retinal (ER) information, visual direction (VD) cue, and optic flow. They found that without both ER and VD, participants showed a greater heading error even in the presence of optic flow. They hence suggested that optic flow alone is insufficient for steering. In contrast, participants could accurately steer toward the goal in the presence of very weak optic flow as long as both ER and VD were present. This implies that humans may mainly rely on the visual direction cue for self-locomotion. That said, their work did not rule out the significance of optic flow since they found that the addition of optic flow improved participants' overall steering performance. Later, a follow-up study done by Li et al. confirmed that with dense optic flow participants reacted faster to heading errors (Li and Cheng 2011a). Li et al. also discovered that with richer optic flow, participants could better correct heading errors caused by pseudo-random perturbations (Li, Stone et al. 2011). In a more recent experiment, Li et al. confirmed that both visual direction and optic flow are used in steering but humans react faster to visual direction (Li and Niehorster 2014). In summary, a number of studies confirmed that both visual direction and optic flow are used for self-locomotion.

Nevertheless, many of those studies primarily focused on investigating steering errors (e.g. heading deviations) in flow fields. This kind of investigation usually assumes that participants could always achieve the task goal (e.g. steering towards a target), but the possibility that, even for the same task, participants might show different steering behaviour according to visual stimulus presented in the flow field was overlooked. Because steering is an active task, humans are likely to choose different strategies if different visual stimuli are presented. For example, it has long been found that drivers will reduce speed to compensate temporary loss of visual feedback (Senders, Kristofferson et al. 1967). More recently, it is also found that on rough road surfaces cyclists spend great attentional resources on monitoring proximate road properties (Vansteenkiste, Zeuwts et al. 2014). This is generally in line with an early study conducted by Wilkie and Wann that found participants actively choose gaze strategies for a steering-through-slalom-gates task (Wilkie, Wann et al. 2008). In their study, they let participants to steer through a series of slalom gates and controlled fixation (i.e. force participants to switch their fixation at a certain point of time) and visibility of gates (i.e. remove gates at a certain point of time). They found that in a free gaze condition, to achieve an unimpaired performance participants tended to choose a time-window of 1 ~ 1.5s for switch of fixation, that is 1 ~ 1.5s prior to passing the upcoming gate the next gate appears and the upcoming gate disappears. In addition to this discovery, they also found that if gates remain visible at all times the manipulations of fixations did not significantly impaired steering performance. In contrast, if gates were removed, only switch of fixations at a later time point could participants achieve comparable steering performance. As a result, one might expect that if steering strategy is tightly associated with the visual stimulus provided, and that this in turn, reflects whether the visual stimulus offers a safe, comfortable control of steering. In this pilot experiment, we asked participants to steer toward targets in three types of environments: a). plain environment (visual direction only); b). ground plane (visual direction + optic flow); c). normal road texture (visual direction + optic flow + road edges). Instead of using a single post as a target, we asked participants to drive through a set of gates. Previous work has extensively investigated humans' performance in steering towards a target, but going through gates are different in several aspects. First, the width of the gate limited the range of angle at which a vehicle could pass through. In this case participants had to adjust the vehicle in order to drive through each gate successfully. That is, this experiment was a more difficult task than reaching a single post. Second, although participants could choose to pass through each gate at any possible heading angle, it would be more comfortable for them to pass gates head-on (i.e. a head-on arrival guarantees a safe pass). Hence the angles at the moment of arriving at each gate reflect whether participants could align the vehicle's heading with the direction of gate in the given environments. A similar slalom-gates-passing study was conducted early by Wilkie and Wann (Wilkie, Wann et al. 2008). However, our experiment is different from theirs primarily due to that we provided three different environments to participants, each of which had different combination of visual cues (optic flow, visual direction, road edges).

Method

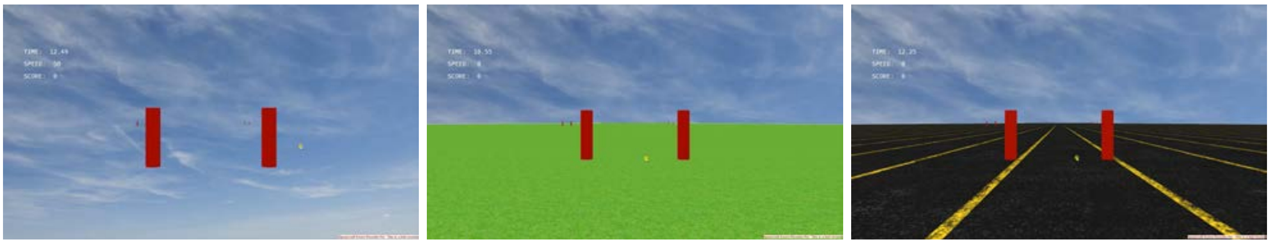

Figure 1 illustrates all three environments used in this experiment. Left: the plain environment; Mid: the ground plane environment; Right: the normal-road environment. Please note that the background (the blue sky) was a static texture providing no heading information at all.

Three environments were used in this experiment, namely plain environment, ground plane, and normal road (Figure 1). The plain environment provided only visual direction to gates. The ground plane provided dense optic flow, integrable trajectories, and visual direction to gates. The richest information was presented by the normal-road environment since it provides additional road edges. The scene was rendered by a program developed by the author, as described in Chapter 1. A Panasonic RZ-470 projector running at 60Hz was used to display the scene. The screen provided a resolution at 1920 × 1080 and a field of view at 69^o (horizontal)× 42^o (vertical). Participants sit in front of the screen (about 2.5 meters away from the screen) and used a Logitech MOMO force-feedback steering wheel to control the simulated vehicle.

This experiment was blocked by virtual environments used (Table 1). The order of blocks was the same for all participants: a). Block 1 = plain environment; b). Block 2 = ground plane; c). Block 3 = normal road. In each block participants repeatedly went through same environment with three different speeds (i.e. 50 km/h, 75 km/h, 100 km/h). The order of speed was counterbalanced between participants. In each trial, participants first drove the vehicle with normal acceleration dynamics, and then drove the vehicle with rate control dynamics. Vehicle's shifting speed for the rate control dynamics was up to 21 m/s, depending on steering wheel angle. Vehicle's wheel angle for the acceleration dynamics was up to 42.5 degree/s, depending on steering wheel angle.

In this experiment, participants were instructed to try not to collide with the gates. In case a collision was occurred, the vehicle stopped moving just as in real world a car would be stopped by an obstacle. The participant then had to steer the vehicle to a non-collision direction to make the vehicle move again. This process generally created a 'struggling' situation for participants if a collision occurred. As a consequence, participants would tend to align the vehicle to the direction of the gate to ensure they can safely (without collision) pass each gate. The visibility of gates was controlled in such a way that only 2 gates (the current, upcoming gate and the next gate) could be seen at a time. Nonetheless, at the very beginning of each trial, participants could see an extra gate (the very first gate 1s' driving away from the vehicle). The very first gate merely acted as a reminder for participants for their tasks and did not need any control of steering to pass it.

Table 1 Lists all blocks and trials.

	Trial 1	**Trial 2**	**Trial 3**
Block 1	Plain / Speed A Acceleration + Lateral	Plain / Speed B Acceleration + Lateral	Plain / Speed C Acceleration + Lateral
Block 2	Ground Plane / Speed A Acceleration + Lateral	Ground Plane / Speed B Acceleration + Lateral	Ground Plane / Speed C Acceleration + Lateral
Block 3	Normal Road / Speed A Acceleration + Lateral	Normal Road / Speed B Acceleration + Lateral	Normal Road / Speed C Acceleration + Lateral

In total, there were 9 trials (3 trials/block × 3 blocks) in this experiment. In each trial, there were 13 gates for participants to drive through. Gates were placed vertically 10 seconds' driving away and horizontally 35 meters apart (either right or left, randomly chosen) from each other. As a result, in any given trial the angle between two consecutive gates depended on the speed of that trial. For example, for trials at speed = 50 km/h gates were put vertically 139 meters (10s' driving) and horizontally 35 meters away from each other, resulting in an angle of 14^o between two consecutive gates. For trials at 75 km/h the angle was 10^o. For trials at 100 km/h the angle was 7^o. The first gate was always positioned less than 1s' driving away from the vehicle's starting position. The first gate acted as a reminder for participants about the task. The data recorded before passing the first gate was ignored. Every gate was placed in such a way that its frontal plane was perpendicular to global Y-axis (Y-axis pointed towards straight ahead). The width of each gate was 4m. The dimension of the vehicle was 1.7m in width and 4.7m in length. Consequently, participants could only go through each gate at heading angle from 0º ~ ± 25º (relative to the global Y-axis, negative = right, positive = left). At the beginning of each trial, the vehicle pointed straight ahead and remained static until participants pressed an embedded button on the steering wheel. Once the button was pressed, the vehicle moved at a constant speed. Participants then had to steer the vehicle to go through each gate. No other instructions or requirements were given to participants.

Participants

Six participants consisting of 4 males and 2 females were involved in this study. They all had normal or corrected-to-normal vision. They were aged from 21 to 41 and had driving experience of 6.67(M) ± 5.68(SD) years. They were all naïve to the purpose of this study. Before the experiment, participants were given 3 minutes to practice. Only acceleration dynamics was used for practice.

Analysis

In this experiment participants were free to choose any trajectory to cross each gate, bringing a considerable amount of difficulties to analyse the data. Because of this, we used heading on arrival, heading changes, and frequency analysis to measure participants' steering movements. Be aware that it is not possible to analyse the heading on arrival and heading changes for the rate control dynamics because in this case the vehicle's heading always remained unchanged. Hence the analysis of heading on arrival (both unsigned and signed) and heading changes are only available for vehicle with the acceleration dynamics. The traditionally favoured heading error or RMS of heading error would be impractical in this experiment because participants did not have to follow any specific trajectory. There was no baseline to measure participants' "heading error".

Results

Unsigned Heading on Arrival and Heading Changes

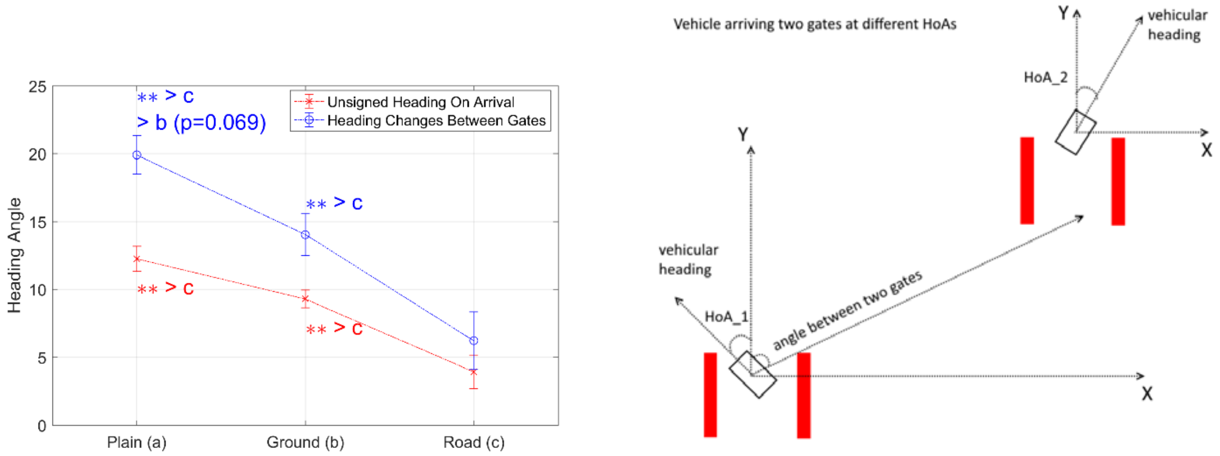

Figure 2a (Left) and 2b (Right). Figure 2a illustrates the unsigned *Heading on Arrival (Red) and Heading Changes between two consecutive gates (Blue). Error bars are SE. “**” indicates 0.01 level.* Figure 2b *explains Heading on Arrival (i.e. HoA_1 and HoA_2) and Heading Changes (HC = HoA_2 – HoA_1).*

We first analysed unsigned heading on arrival and heading changes between two consecutive gates. Figure 2b shows the definition of Heading on Arrival and Heading Changes. Heading on Arrival is the heading angle at the moment of the vehicle arriving at a gate. Heading Changes are the changes in heading angles between last heading on arrival and current heading on arrival. As shown in Figure 2a, the unsigned heading on arrival (HoA) for plain environment was 12.261 (M) ± 0.926 (SE), for ground plane was 9.296 (M) ± 0.648 (SE), and for road was 3.925 (M) ± 1.229 (SE). A repeated measures Anova was performed on unsigned HoA over three environments, revealing that the effect of environments was significant, F(2, 10) = 33.219, p < 0.001. Further pairwise comparisons indicate that unsigned HoA for road was significantly smaller than that for ground plane (p = 0.002) and that for plain environment (p = 0.003). The results generally suggest that with more visual cues presented participants tended to reach each gate head-on.

In addition to HoA, we also investigated Heading Changes (HC) between two consecutive gates. Small HC between two consecutive gates is expected if participants arrived at each gate at similar HoAs. The HC for plain environment was 19.533 (M) ± 1.292 (SE), for ground plane was 13.643 (M) ± 1.578 (SE), and for road was 6.262 (M) ± 2.157 (SE). A repeated measures Anova was conducted on HC over three environments, suggesting that the effect of environments was significant, F(2, 10) = 31.644, p < 0.001. Further pairwise comparisons indicate that HC for road was significantly smaller than that for ground plane (p = 0.004) and that for plain environment (p = 0.005). It was also found that HC for ground plane was insignificantly smaller than HC for plain environment, p = 0.069. The results suggest that with more visual information available, participants reached each gate with more consistent HoA. It is worth mentioning that there was a lateral gap between two consecutive gates, as described in Method section (see Figure 2b). The gap essentially acted like a “lane”. As a result, the small HC suggests that participants did a “lane-changing-alike” manoeuvre, which involves an extra straightening phase, during steering from current gate to the next.

Taken together, with less information presented participants reached each gate at a less comfortable, larger heading angle. In contrast, with more information presented participants aligned the vehicle’s heading with the direction of each gate. The difference on HC over different environments suggests that with more visual cues present participants did an extra steering phase to straighten the vehicle’s heading.

Signed Heading on Arrival over Leftward/Rightward Gates

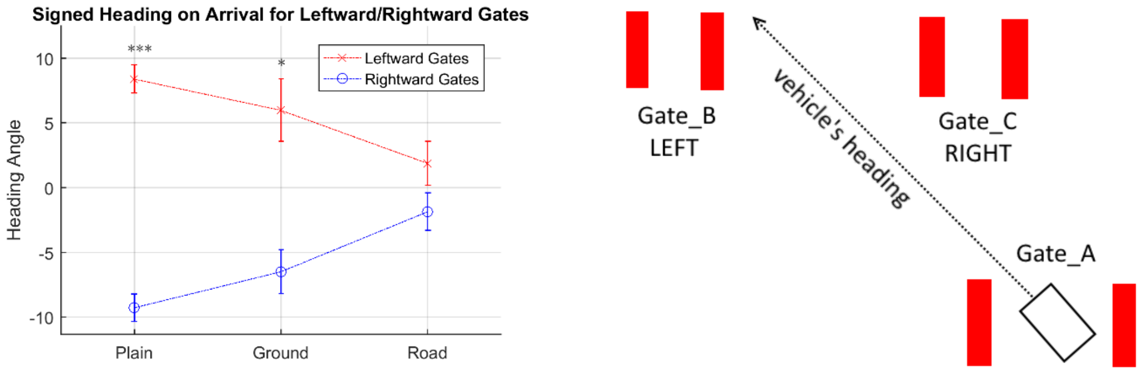

Figure 3a (Left) and 3b (Right). Figure 3a illustrates participants signed heading on arrival at leftward/rightward gates. Negative HoA indicates rightward HoA and positive HoA indicates leftward HoA. Error bars are SE. “” indicates 0.05 level. “***” indicates 0.001 level. Figure 3b explains the definition of leftward/rightward gates.*

In this analysis, we divided gates into leftward gates and rightward gates. Participants’ signed HoAs were analysed for both leftward gates and rightward gates (Figure 3a). Figure 3b explains the definition of leftward gates and rightward gates. A leftward gate is a gate that is to the left of the vehicle’s momentary heading at arrival of the current gate. The same definition applies to rightward gate. As shown in Figure 3b, let Gate_A denote the current gate at which the vehicle just arrived. It is clear that Gate_B is to the left of the vehicle’s heading while Gate_C is to the right of the vehicle’s heading. Hence Gate_B is a leftward gate and Gate_C is a rightward gate. Signed HoA also had two directions: leftward (positive value) and rightward (negative value). A positive (leftward) HoA is to the left of the global Y-Axis and a negative (rightward) HoA is to the right of the global Y-Axis, as can be seen from Figure 2b.

For leftward gates, participants always showed leftward HoAs over all environments: a). 8.391 (M) ± 1.086 (SE) for plain environment; b). 5.982 (M) ± 2.407 (SE) for ground plane; c). 1.883 (M) ± 1.688 (SE) for road. For rightward gates, participants always showed rightward HoAs over all environments: a). -9.272 (M) ± 1.058 (SE) for plain environment; b). -6.489 (M) ± 1.697 (SE) for ground plane; c). -1.860 (M) ± 1.453 (SE) for road. A paired t-test was conducted on those two signed HoAs over environments, revealing that there was a significant difference on HoAs between leftward gates and rightward gates for plain environment, $t(5) = 9.484$, $p < 0.001$, and for ground plane, $t(5) = 3.164$, $p = 0.025$. Nonetheless, such an effect was not found for road, $t(5) = 1.225$, $p = 0.275$.

The results suggest that with less visual feedback (i.e. plain environment and ground plane environment) the direction of HoA was associated with the direction of gates. Most likely, participants mainly relied on visual direction in those environments, leading to participants steering toward gate without any attempt to re-align the vehicular heading with the direction of gate. On the other hand, for environments with abundant information (i.e. road edges) participants did an extra steering phase to straighten the vehicle's heading, leading to the signed HoA irrelevant to the direction of gate.

Frequency Analysis (FFT)

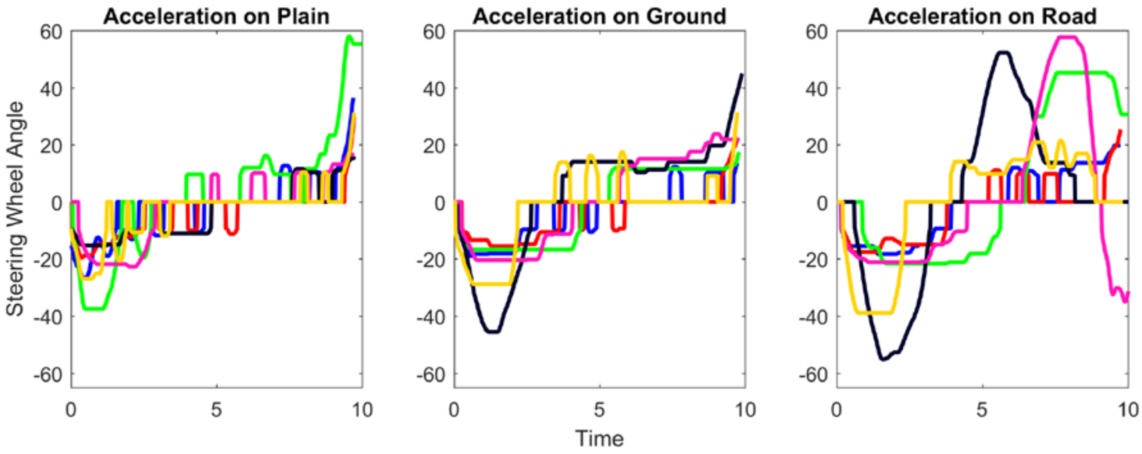

Figure 4a illustrates all participants' steering wheel profiles (colourful lines) during approach of the second gate with the acceleration device. Left: plain environment; Middle: ground plane; Right: road.

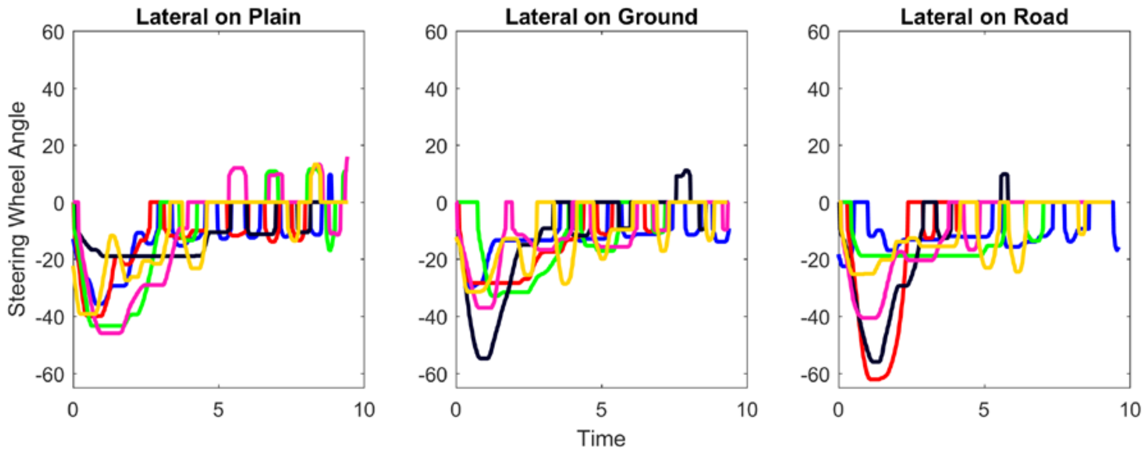

Figure 4b illustrates all participants' steering wheel profiles (colourful lines) during approach of the second gate with the rate control device. Left: plain environment; Middle: ground plane; Right: road.

All the analysis made so far were for the acceleration device only, since they were all heading-related data. In addition to heading-related data, we further analysed steering wheel data for both vehicle dynamics. Figure 4 shows typical steering wheel data during passing the second gate in a trial. As to the analysis, we used Fast Fourier Transform (FFT). FFT results can reflect how participants steered the vehicle in general. For FFT, we calculated energy over different frequencies for both vehicle dynamics. In this experiment the simulator ran at 60Hz, hence the resolution of FFT is from 0 to 30Hz. After simple calculations, we found that the vast majority of energy (~96%) was at frequencies from 0 to 0.5 Hz, consistent with previous work (see the pilot experiment of Study 1). Consequently, this analysis was only on [0, 0.5] Hz.

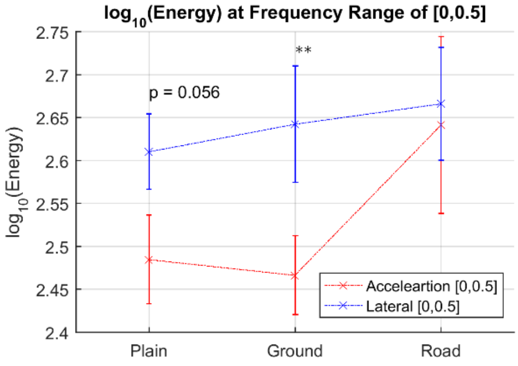

*Figure 5 indicates energy distribution across frequencies for the two vehicle dynamics over three environments. "**" indicates 0.01 level. Error bars are SE.*

Figure 5 shows the results of FFT analysis. For the rate control dynamics, the energy (adjusted to $\log_{10}$) for plain environment was 2.610 (M) ± 0.044 (SE), for ground plane was 2.642 (M) ± 0.068 (SE), and for road was 2.666 (M) ± 0.066 (SE). For the acceleration dynamics, the energy (adjusted to $\log_{10}$) for plain environment was 2.485 (M) ± 0.052 (SE), for ground plane was 2.467 (M) ± 0.046 (SE), and for road was 2.641 (M) ± 0.103 (SE). A paired t-test conducted on energy over two vehicle dynamics for the three environments reveals that: a). for the plain environment, energy spent on the rate control dynamics was insignificantly higher than energy spent on the acceleration dynamics, $t(5) = 2.474$, p =

0.056; b). for the ground plane, energy spent on the rate control dynamics was significantly larger than energy spent on the acceleration dynamics, t(5) = 4.383, p = 0.007. there was no significant difference on energy spent on road between two vehicle dynamics, t(5) = 0.203, p = 0.847.

The results suggest that in general participants spent more energy in steering the acceleration device, opposite to what was found in the pilot experiment in Study 1 (see the pilot experiment of Study 1). This disparity can be explained by the difference between two experiments. The pilot experiment in Study 1 was essentially a lateral position control task, in which a rate control device is more efficient since it controls the rate of changes of vehicle's lateral position. Nonetheless, current experiment was a heading control task, in which participants aimed to a set of gates. Due to the fact that participants could not change the vehicle's heading with the rate control dynamics, they had to laterally shift the vehicle to match each gate in the case of the rate control dynamics. Given the vehicle's shifting speed was up to 21 m/s for the rate control dynamics and the horizontal distance between consecutive gates was 35 meters, participants needed at least 1.7s to move the vehicle to match each gate in the case of the rate control dynamics. By contrast, the vehicle's wheel angle was up to 42.5^o for the acceleration dynamics, participants could change the vehicle's heading drastically within 1s to aim to a gate and then release the steering wheel afterwards. In other words, the acceleration device was more efficient for this heading control task. That said, the energy consumed on road between two dynamics was comparable. This was probably because the extra straightening steering phase conducted by participants on road environment under acceleration dynamics.

Finally, Figure 4a shows that with the acceleration dynamics participants made a lane-change-alike manoeuvre in passing gates in the environment of normal road texture. This is consistent with the results of HoA and HC, both of which suggest that participants made an extra straightening steering phase (a full, bi-phasic lane-change manoeuvre) in passing gates on the road with the acceleration device.

Discussion

We conducted an experiment in which participants were asked to go through a series of gates in different virtual environments, namely the plain environment, ground plane, and normal road. Although we did not give any instruction as to how to pass each gate, participants chose different strategies in different environments. In the plain environment in which visual direction was the only cue, participants arrived at each gate with the largest heading on arrival and made the biggest heading changes between consecutive gates. On ground plane in which both visual direction and optic flow were available, participants showed large heading on arrival but smaller heading changes. By contrast, on a normal road with road edges visible, participants showed the smallest heading on arrival with the smallest heading changes.

Generally, the results suggest that participants did prefer small heading on arrival whenever possible, presumably because small heading on arrival guarantees a safe pass through the gate. Interestingly, on the ground plane where participants were able to perceive both heading and integrated trajectories, they surprisingly showed a relatively large heading on arrival (~10 degree) compared to that on road. Perhaps the cues provided by a ground plane are insufficient for people to make a full straightening phase (i.e. straightening the vehicle to achieve a small heading on arrival). This suggests that despite it being long believed that a ground plane, which provides both visual direction (through its texture gradients) and optic flow, should be sufficient for people to steer toward a target (Li and Warren 2002, Wilkie and Wann 2002, Wilkie and Wann 2003, Li and Cheng 2011a, Kountouriotis and Wilkie 2013, Li and Cheng 2013, Li and Niehorster 2014), the conduct of a straightening phase requires more information. In this experiment, only on the road providing lane lines did participants conduct a straightening steering phase to reach every gate head-on. This is also confirmed by the results of signed heading on arrival which shows that in both the plain environment and ground plane participants demonstrated steering bias associated with the direction of the gates. The steering bias was likely due to the lack of a straightening phase --- with visual direction the main source of information that participants used to steer toward the direction of gate.

During everyday driving, a straightening phase is needed in many situations such as during a lane change. Inability in making a straightening phase on the ground plane raises the question of whether rich optic flow provides enough cues for lane-changing tasks. Although it has long been assumed that humans can locate heading within an accuracy of 1~2 degrees in various situations (Lappe, Bremmer et al. 1999, Li and Warren 2000, Li and Warren 2002, Li and Warren 2004), recently Kountouristis (Kountouriotis and Wilkie 2013) et al. suggest that an accurate heading perception (e.g. threshold at 2 ~ 4 degrees) does not necessarily lead to an accurate active steering performance (e.g. heading errors was significantly larger than 5 degrees). Other visual cues such as road edges may be more important in general steering (Robertshaw and Wilkie 2008, Kountouriotis, Floyd et al. 2012).

Finally, we should mention that participants did not show any difficulty in steering through the gates with a lateral position control device, since the vast majority of their energy was spent on low frequencies from 0 to 0.5Hz. In addition, we also found that while a rate control device is more efficient in a lane-keeping task (see the plot experiment in Study 1), it is less efficient in a heading control task.

Experiment 2 Lane Change in Optic Flow

Introduction

Despite many years of investigation, the precise set of cues required by humans to control their direction of travel remains a subject of debate. One cue to have attracted particularly intense debate is optic flow. It was Gibson (Gibson 1950, Gibson 1958) who originally proposed that humans can use the "focus of expansion" (FoE) of the optic flow field to locate where they are heading. His proposal has been supported by the discovery that humans can use optic flow to estimate heading to within 1 or 2 degrees, so long as it contains no rotational component (Warren, Morris et al. 1988). This level of accuracy would suffice to safely navigate under various situations (Cutting 1986). The main criticism of flow-based heading control is that pure translation without rotation (caused by eye movements or body/path rotations) is unlikely to occur in everyday life. In natural settings, humans almost always move their eyes at the same time as they move through their surroundings, resulting in optic flow that is more complex. In response, many efforts have since been made to investigate how optic flow might be decomposed into translational and rotational components (Warren and Hannon 1988, Warren and Hannon 1990, Perrone 1992, Royden, Banks et al. 1992, Van den Berg 1993, Banks, Ehrlich et al. 1996, Van den Berg 1996, Ehrlich, Beck et al. 1998). While several of these authors favour a pure retinal-based flow solution, Royden, Banks, Enrilich and colleagues argued that extra-retinal information such as oculomotor signals are necessary. The most recent literature suggests that performance is best when human observers have access to both retinal and proprioceptive cues (Li and Warren 2000, Li and Warren 2002, Li and Warren 2004).

In contrast to the FoE hypothesis, other authors have suggested that it is "visual direction" (defined by the visual angle between one's body central line and his/her target) that guides locomotion (Rushton, Harris et al. 1998, Rushton and Salvucci 2001). The idea is related to Llewellyn's target-drift idea, which proposes that human observers can reach their target by continuously changing their direction of travel to cancel the drift of a target (Llewellyn 1971). In one experiment Rushton, Harris et al. (1998) asked participants to reach a target a few meters away while wearing prismatic glasses. The authors reported that participants walked toward the target in curved trajectories, consistent with the predictions of the "visual direction" hypothesis. However, subsequent studies have argued against this conclusion (Wood, Harvey et al. 2000, Harris and Carre 2001, Warren, Kay et al. 2001, Bruggeman, Zosh et al. 2007). In their follow-up studies, these researchers successfully showed that optic flow was still being used in environments consisting of textures and/or reference objects. It is currently generally accepted that both optic flow and visual direction cues contribute to human locomotion (Wood, Harvey et al. 2000, Harris and Carre 2001, Warren, Kay et al. 2001, Wilkie and Wann 2002, Wilkie and Wann 2003, Wilkie and Wann 2005, Li and Niehorster 2014).

Building on the concepts developed above, more recent work has proposed that drivers may use ‘retinal flow’ directly, without the need to explicitly retrieve heading (Wann and Land 2000, Wann and Swapp 2000, Wilkie and Wann 2006, Wilkie, Wann et al. 2008, Wilkie, Kountouriotis et al. 2010). In particular, Wann, Land, and colleagues showed that if one fixates a target 1 to 2 seconds ahead, flow lines emanating from the target will be curved if one oversteers or understeers relative to the target. Since the direction of curvature indicates the direction of steering error, one can steer towards a target simply by perceiving those flow lines. This solution has been dubbed the “future path” (FP) strategy. This strategy does rely on optic flow, but raises the question of whether it is necessary to retrieve heading when the alternative FP strategy offers a simpler, more immediate solution. Wann et al. also showed that accurate heading estimation during periods of translation and rotation place considerable demands an observer’s attention. They argue that this would, in practice, be too demanding for practical everyday locomotion (Wann, Swapp et al. 2000). But the debate is far from over. Li and colleagues, for example, suggested that humans tend to use heading, not FP, to steer towards a target (Li and Cheng 2011a). They claimed that heading estimation is more robust than FP since they found that the former was not affected by different types of optic flow or different directions of gaze, whereas the latter was susceptible to changes of gaze direction (Li and Cheng 2011b). Meanwhile, some popular dynamical models of locomotion successfully incorporated heading estimation and generated smooth and natural locomotion behaviour (Fajen, Warren et al. 2003, Fajen and Warren 2003, Fajen and Warren 2007, Fajen 2013). Taken together, it is still a matter of debate whether heading estimation or future path is used during locomotion. For a more comprehensive review of this topic see Lappe, Bremmer et al. (1999) and Lappi (2014).

The evolution of experimental design

In the past, many of the studies of optic flow involved participants passively experiencing motion in a flow field (i.e. no interaction between participants and the scene). While this type of experiment has led to many significant discoveries, the approach cannot offer a complete investigation of human locomotion in optic flow. In natural settings, humans actively interact with the scene and they often have an expectation of their on-going actions and the resultant optic flow. For example, a driver would know in advance that his/her retinal images are going to be shifted if he/she is about to make a turn. Such predictions or expectations can form an important part of an internal control model (Kawato 1999, Shadmehr, Smith et al. 2010), or can act as a simple heuristic or mapping strategy (Zhao and Warren 2015). One line of evidence for this is in the case of lane-changing where it has been demonstrated that the internal predictions/expectations are incorrect (Wallis, Chatziastros et al. 2002, Cloete and Wallis 2009). Systematic errors in steering of this kind suggest that humans have expectations of their ongoing actions. Nonetheless, this prior knowledge is not reflected in experiments using passive observation of optic flow and this represents a significant limitation of previous studies. In interactive environments, one can investigate the use such prior knowledge to generate actions in a way that the corresponding pattern of optic flow matches ones expectations. Interactive scenarios provide rich internally (predictive) and externally (multi-sensory) derived information capable of aiding the attribution of changes in flow to the appropriate source. In this instance, changes in heading versus those caused by head or eye rotation can be dissociated because they are being generated by the observer themselves.

For this reason, more recent optic flow studies have begun to employ interactive environments, requiring participants to steer towards a target (e.g. (Li and Warren 2002)). However, in these settings it is diffcult to completely eliminate the effects of a visual direction cue caused by the addition of a target and/or other objects. Rushton (2008) found that by adding objects into the scene, more cues such as target-drift, the relative position of objects, and changes in persepctive all become available; providing extra-flow information to participants. Some studies (e.g. (Li and Cheng 2011a)) have attempted to artifically fix the target-heading angle to eliminate visual direction cues. While they might indeed eliminate the visual direction cue, it also resulted in a very unnatural environment for participants, questioning ecological validity.

In the same year Li and colleagues (Li, Stone et al. 2011) published results from a study in which participants were required to actively control a simluated vehicle’s heading in the face of pseudo-random perturbations in heading. On the basis of their study, the authors concluded that the “velocity field alone is sufficient to support closed-loop control”. Although valid in the context in which they conducted their study, one could argue that the task only requires a realtively simple uni-phasic manoeuvre since the task can be solved by adjusting heading iteratively to the left and right in occasional stepwise movements, rather than continuously. Wallis and colleagues have shown that a uni-phasic manoeuvre of roughly appropriate amplitude and duration can be conducted without the need for any visual feedback at all (Wallis, Chatziastros et al. 2007). What Wallis and colleagues work also reveals, however, is that a minor increase in task complexity, to a biphasic manoeuvre, suddenly produces systematic errors in the absence of visual feedack (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009, Xu, Wallis et al. 2014). The idea of this paper is to utilise this result to test the role of optic flow in heading control in the absence of other cues.

The revealing case of lane changing

Before launching into the methodological detail of this study it is useful to quickly recap on the lane-changing results which Wallis and colleagues have reported. In the presence of full, uninterrupted visual feedback, a typical lane-change manoeuvre can be characterized as a bi-phasic manoeuvre (Figure 1a). Changes of steering wheel angle over time closely resemble a sinusoidal function (Figure 1a, also see (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Xu, Wallis et al. 2014)). Early studies of lane changing and lane correction suggested that the manoeuvres could be conducted in the absence of visual feedback (Godthelp 1985, Hildreth, Beusmans et al. 2000), leading to the proposal that the entire, bi-phasic steering motion is prepared before the manoeuvre begins. However, in 2002 Wallis and colleagues (Wallis, Chatziastros et al. 2002) reported the surprising fact that removing visual feedback actually led to a systematic error, as described in Figure 1b. Without visual feedback, almost all participants only completed the first phase of the bi-phasic movement, leading to the driver steering off the road in the direction of the lane change.

One possible reason for this failure might be that this effect is due to a failure of spatial memory. However, Cloete and Wallis showed that if drivers are asked to conduct an obstacle avoidance manoeuvre, they produce a lane change instead! This would seem to imply that a drivers’ spatial memory is capable of supporting a lane change without feedback if the driver chooses to implement the biphasic steering-wheel movement (Cloete and Wallis 2009). Rather than accounts based on memory, recent papers on the topic have concluded that the problem instead lies in the fact that drivers conceptualize the steering wheel as a rate control device for lateral position, rather than the acceleration device that it really is (Cloete and Wallis 2009, Xu, Wallis et al. 2014). In other words, participants mistakenly believe that they can change a vehicle’s lateral position directly though rotation of the steering wheel. In fact, rotating a steering wheel changes the vehicle's front wheel angle which in turn leads to a change in the vehicle's heading over time, making a steering wheel a second-order control device for lateral position. So why do drivers usually get it right? Presumably, in the presence of visual feedback the steering error is rapidly perceived by the drivers, even though its source remains opaque to them. The question here, is whether optic flow can provide the crucial information required to correct the erroneous assumption that lead to the erroneous behaviour seen in the absence of visual feedback. If drivers utilize flow to track heading changes during normal driving, the expectation is presumably 'yes'.

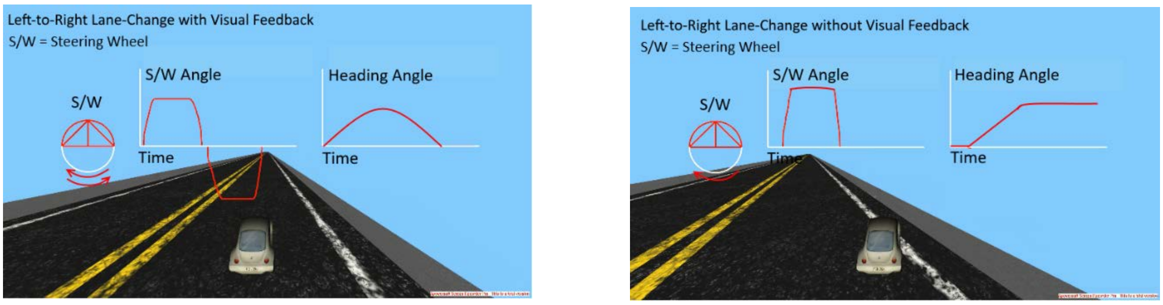

Figure 1a(Left) and 1b(Right) illustrates the pattern of changes of steering wheel angle and heading angle during a typical lane change (change from left lane to right lane) with and without visual feedback. This pattern was confirmed by Wallis and his colleagues (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Xu, Wallis et al. 2014). In their experiments, a two-lane road was displayed either with full visual feedback (1a), or in darkness (1b) i.e. with no visual feedback.

Current Study

In this paper, we aimed to investigate whether optic flow is sufficient to complete a lane-change or whether the systematic errors, seen in the absence of any feedback, would reoccur. To that end we first examined whether participants could perceive heading accurately using our stimulus and apparatus. Then we asked participants to conduct lane changes in various flow fields and compared their performance under three conditions: with full visual feedback, with optic flow, and in the absence of any visual feedback.

In practice, optic flow can take different forms depending on its duration and source. In this paper we follow Li et al. (Li, Stone et al. 2011), by considering three types of flow information:

- **Dynamic optic flow** consisting of a cloud of random dots, in which every dot is deleted and replaced by another in a random location after a certain period of time (6 frames, about 100ms in this study). The 'lifetime' of the dots matched that used by Li et al. (Li, Sweet et al. 2006). This type of flow was used recently in several studies (e.g. (Li, Sweet et al. 2006, Li, Chen et al. 2009, Li, Stone et al. 2011)). It is intended to prevent extensive motion tracking.

- **Static optic flow** consisting of a cloud of random dots, in which dots persist throughout the duration of the trial. There is a long history of using this type of flow field in the literature (e.g. (Banks, Ehrlich et al. 1996, Li, Sweet et al. 2006, Li, Chen et al. 2009, Li, Stone et al. 2011)).
- **Ground plane** consisting of a Gaussan-filtered texture, which provides more information than a cloud of dots. In principle, many path estimation strategies require a ground plane, e.g. locomotor flow lines (Lee and Lishman 1977) and future path strategy (Wann and Land 2000, Wann and Swapp 2000), since they all need to integrate trajectories. Ground planes have likewise featured in many previous studies (Li and Warren 2000, Li and Cheng 2011b, Kountouriotis and Wilkie 2013, Li and Cheng 2013).

Because road lanes are only visible in the full visual feedback condition, here we define a proper lane change in optic flow as a “bi-phasic” manoeuvre (Figure 1a) rather than moving the vehicle precisely into the destination lane. In other words, we do not expect participants to achieve precise control of the vehicle’s lateral position in optic flow. Rather, we expect to see their intention to conduct a second, return phase during lane change.

Because we are using a novel, large-screen projection system with very wide field of view, we also tested the ability of our participants to estimate their heading using a range of flow-field stimuli. Details of the heading perception experiment can be seen in Appendix A. The results were consistent with previous studies showing an accuracy of heading estimation in the order of 1~2^{o} (e.g. (Warren, Morris et al. 1988, Foulkes, Rushton et al. 2013)).

Method

Contents and Procedure

The method was based on a simple hypothesis: if optic flow is sufficient for lane change one could expect a bi-phasic manoeuvre in optic flow, otherwise a uni-phasic manoeuvre is expected. Given that drivers are likely to conduct bi-phasic lane change with full visual feedback and uni-phasic lane change with no visual feedback, one could compare steering behaivour among optic flow, full-visual-feedback condition, and no-visual-feedback condition. If optic flow is sufficient for lane change, we would expect participants to display similar lane change manoeuvre between flow environments and full-visual-feedback condition. Otherwise, we would see simliar lane change manoeuvre being conducted between flow environments and no-visual-feedback condition. Based on this idea, we conducted two experiments, with different flow environments used. The initial experiment (Exp. 1) focused on the impact of providing dynamic vs static flow information and contrasting it to performance during full visual feedback and no visual feedback. The four conditions were run in four separate blocks of trials (see Table 1). Block 1 and 4 acted as baseline conditions with either full visual feedback or no visual feedback present during the manoeuvre. In contrast, during Blocks 2 and 3 various optic flow conditions were tested (Table 1). Block 1 and 4 were identical in appearance but Block 1 served as a pre-flow block and provided a baseline for subsequent analysis. Block 4 was used as a post-flow block, aiming to investigate whether participants' behaviors had changed after exposure to the optic flow blocks (Block 2 and 3). In particular, we were curious to know if participants could learn to alter their naïve behaviour through exposure to the optic-flow blocks. The two optic flow blocks were presented in counterbalanced order across participants. In each block, there were 16 left-to-right lane changes and 16 right-to-left lane changes presented in random order. Procedures for the second experiment (Exp. 2) were identical to the first except that the dynamic flow stimulus was replaced with the ground plane stimulus (Table 1).

During each trial, the vehicle was first put onto a randomly chosen lane (e.g. left lane or right lane) with full visual feedback. The vehicle remained stationary until participants pressed a start button embedded in the steering wheel. Hence participants were afforded the opportunity to look around the virtual enviroment before starting the vehicle. After pressing the button, the vehicle ran at a constant speed of 70 km/h. Participants then had 4 seconds to get ready, after which they were reminded by a message on screen to conduct a lane change in a given direction (e.g. change to the left/right lane). 12 seconds were given to the participant to complete the manoeuvre (all in the presence of full visual feedback). After the first lane change, participants continued to move forwards. Then, after 2 seconds, feedback was switched to the condition being run in that particular block (e.g. no feedback, static flow etc.). Participants were then instructed via the same on-screen message to conduct a lane change in the opposite direction to the one they had just completed. Once again, 12 seconds were given to participants to complete the manoeuvre. After each trial, no feedback was given to participants as to their lane-change performance. In total, there were 2 (lane-change directions) × 16 (repetitions) × 4 (blocks) = 128 lane changes. For analysis, the data were collapsed over the left and right lane changes.

Importantly, during each trial of this experiment, participants always carried out their first lane change with full visual feedback, before going on to experience only flow or no feedback (Table 1). Therefore, for the total number of 128 lane changes in each experiment, half of them were conducted with full visual feedback, mimicking the conditions used by Wallis, Chatziastros et al. (2002). This approach helped eliminate any creeping sense of disorientation that might otherwise have accumulated across trials.

***Table 1** demonstrates the procedure of each trial in this experiment.*

Block	**Procedure of Each Trial** (numbers = duration in seconds)		Presence
1	First lane change in full visual feedback (12’)	Second lane change in no visual feedback (12’)	Exp. 1 + Exp. 2
2	First lane change in full visual feedback (12’)	Second lane change in static optic flow (12’)	Exp. 1 + Exp. 2
3	First lane change in full visual feedback (12’)	Second lane change in optic flow (12’)	Optic flow is either “dynamic flow” in Exp. 1 or “ground plane” in Exp. 2.
4	First lane change in full visual feedback (12’)	Second lane change in no visual feedback (12’)	Exp. 1 + Exp. 2
Procedure of each trial: 4’ (get-ready) + 12’ (first lane change in full visual feedback) + 2’ (get-ready) + 12’ (second lane change in changed visual feedback)			

Stimulus and Apparatus

Testing was conducted in an environment created using custom software written by the lead author. Coding was in C++ combined with OpenSceneGraph libraries. A deskside PC, comprising an i5 quad-core CPU and 8GB RAM and GTX 780 graphics card, was used to run the program. A custom-built projection system (Figure 2) consisting of three Panasonic RZ-470 projectors running at 60 Hz and a wide and curved screen (12m (wide) × 3m (tall)) was used to render the scene. Specialist software (IMMERSAVIEW) was used to warp the image onto the curved screen, producing a 160^{o} (Horizontal) × 45.5^{o} (Vertical) visual area comprising 5760 × 1080 pixels. Participants were seated about 2.7 meters aways from the surface of the screen approximately at the screen’s centre of curvture. Participants used a force-feedback Logitech MOMO steering wheel to steer.

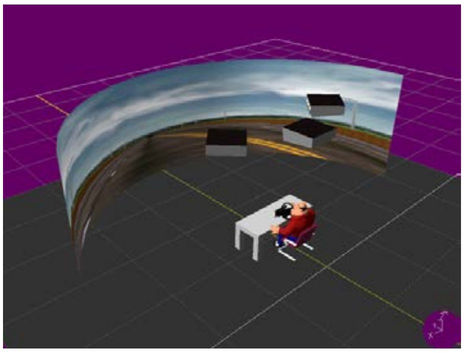

Figure 2 demonstrates the system used in this study.

For this experiment, we had three types of optic flow fields: static optic flow, dynamic optic flow, and ground plane. The static optic flow (Figure 3a) consisted of 80,000 white dots with radii of 3mm (4X anti-aliasing), approximately 0.05° in visual angle. Those 80,000 dots were randomly distributed across space with the depth range of 1000 meters. Due to view frustum, around 11,000 dots were visible in any one frame. The dynamic optic flow (Figure 3a) was identical to static optic flow except the dots had a limited lifetime (100ms). The limited life-span was achieved by deleting all dots and redrawing them at random positions every 6 frames. As a result, the dynamic flow gave participants a sense of motion but no integrable information, whereas the static flow provided certain integrable information such as the dots' acceleration. The ground plane (Figure 3b, Left) consisted of a Gaussian-filtered texture. Figure 3b (Right) illustrates the road used in the full visual feedback condition.

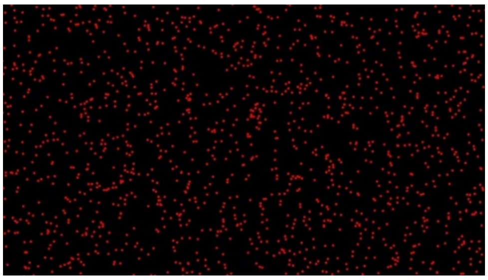

Figure 3a demonstrates the static optic flow and dynamic flow. For clarity, all dots have been magnified and rendered in red.

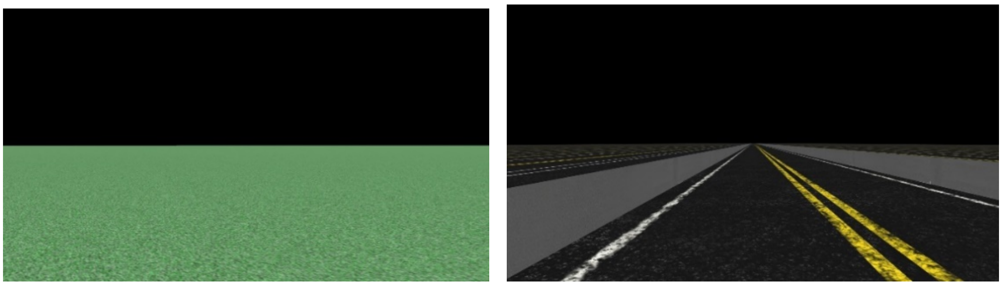

Figure 3b presents the textures in the ground plane (Left) and Road (Right). The high-resolution road texture (4096 × 4096) used in under the full visual feedback condition was created by Krist-Silvershade and was downloaded from the DEVIANT-ART website.

Analysis

During the experiment, lapses in attention to the task led to some trials being excuded from analysis (Exp. 1, 5%; Exp. 2, 3%). Typical issues included not moving the steering wheel at all, changing lanes in the wrong direction, or holding the steering wheel at a particular angle at all times.

In describing the analysis, we employ the following labels to represent different types of visual feedback: “Road” represents the full visual feedback condition in all blocks and “Dark-Pre” represents the case of no visual feedback in the initial, baselining block (Block 1). “Static” represents static flow and “Dynamic” represents dynamic flow. “Ground” represents the ground plane condition. “Dark-Post” represents the no visual feedback condition carried out at the very end of the experiment (Block 4). Therefore, “Road” contains all 64 lane changes with full visual feedback, whereas the rest (“Dark-Pre”,” Static”, “Dynamic”, and “Dark-Post”) contain 16 lane changes under each of the corresponding visual feedback conditions.

Data analysis of the lane-change experiments centred on two measures: (i) the Return Ratio and (ii) RMSE. The Return Ratio (RR for short, see Figure 4 for definition, see also (Macuga, Beall et al. 2007, Wallis, Chatziastros et al. 2007)) was used to measure whether a participant conducted a lane change successfully. RR is a convenient metric for quantifying the return phase of a lane-change manoeuvre. RR is defined as the ratio of the heading change seen during the return (second) steering movement, divided by the heading change seen during the outward (first) steering movement. If H_{peak} denotes the peak value of heading, and H_{final} the final value of heading, we have

$$\mathrm{RR} = \frac{H_{peak} - H_{final}}{H_{peak}}$$

Obviously, a RR close to 1 indicates an almost perfect lane change (as is Figure 4), while RR close to 0 indicates a lane change with little or no Return Phase (as is Figure 1b). Again, we have to emphasize that “correct lane change” in this paper does not require precise control of the vehicle’s lateral position. RR only measures whether a bi-phasic manoeuvre is conducted, in other words, if the vehicle’s heading is returned after the first phase of lane change. RR indicates nothing in terms of vehicle’s lateral position. We used RR only to measure whether a manoeuvre is bi-phasic or not.

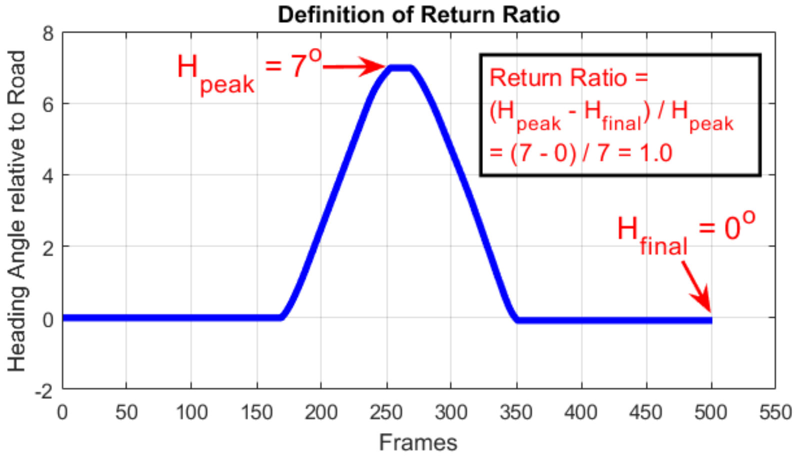

Figure 4 Heading changes for one subject during a lane-change with full visual feedback. The Return Ratio (RR for short), is defined as $(H_{Peak} - H_{Final}) / H_{Peak}$.

Besides Return Ratio, we also used Root Mean Square Error (RMSE) to analyse steering wheel profiles (Figure 5). RMSE was used to compare two steering wheel profiles (i.e. steering wheel profile A and B). Let Y_{A_i} denote steering wheel angle at ith frame of steering wheel profile A, and let Y_{B_i} denote steering wheel angle at ith frame of steering wheel profile B. We have

$$\text{RMSE} = \sqrt{\frac{\sum(Y_{A_i} - Y_{B_i})^2}{n}}$$

where n denotes the total number of frames. A small RMSE between two steering wheel profiles means they are similar to each other, while a large RMSE indicates there is an evident difference between the two. With RMSE analysis, one can know whether participants' steering-wheel profiles under each condition were more similar to those under the "Road" condition or "Dark-Pre". One might expect that in optic flow, subjects will produce a lane-change manoeuvre close to a "perfect" one (the one produced in "Road") rather than a "wrong" one (the one produced in "Dark-Pre"). Because RMSE is affected by amplitude of steering wheel angle, all steering wheel profiles were normalized (ranging from -1 to 1) as shown in Figure 5, before conducting RMSE. Some other adjustments to the steering wheel data were also implemented for RMSE analysis. Details of such adjustments can be seen in the Appendix C. Again, the measurement of steering profile is not dependent on the vehicle's lateral position. One can conduct two very similar steering movements but end up in very different lateral positions. For example, if one conducts two bi-phasic manoeuvres of differing amplitude but otherwise the same shape, e.g. first one of small amplitude and the second of large amplitude, the vehicle's lateral position will be very different after each manoeuvre, but the two normalized steering profiles will be exactly the same and the RMSE will be 0. By using RMSE, we were not interested in whether participants precisely moved their vehicle to the adjacent lane because this may be very difficult to achieve without visual feedback. Instead we were curious to see if participants attempted to complete a bi-phasic manoeuvre. In other words, whether they successfully regained their original heading (parallel to the centre-line of the straight road) or not.

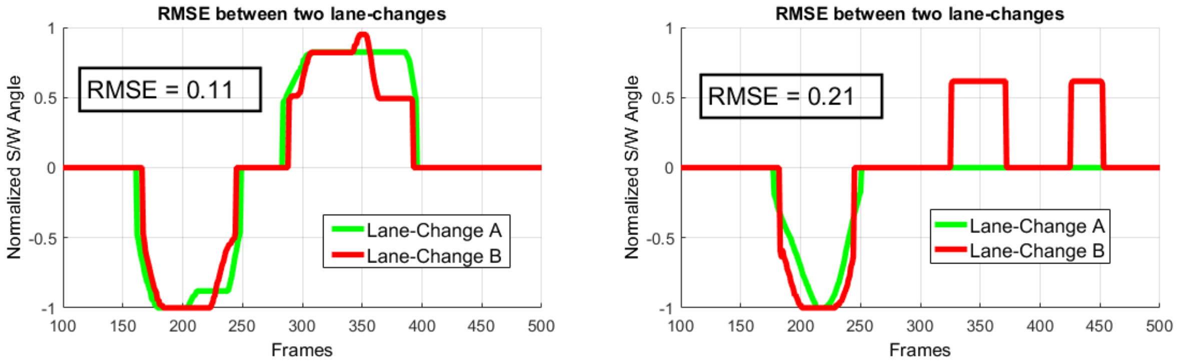

Figure 5 RMSE definition and two examples. Left graph indicates a small RMSE because of the similarity between the two steering wheel profiles, while the right-hand graph indicates the opposite.

Participants

We recruited participants from three universities in Brisbane, Australia. Participants were paid $15 per hour. This study was approved by the Human Research Ethics Committee of University of Queensland. Before testing began, participants were given the opportunity to practice at least 8 lane changes with full feedback. Participants then all began with a Dark-Pre block (Block 1).

Only participants who showed systematic errors during this first block (Figure 1b, the term “naïve” is used to describe those participants) were recruited for further study. This is because if participants already showed a reasonably good ability to change lanes with no visual feedback, it is unnecessary to test them again in optic flow. For this purpose, an initial screening process was set up to filter out participants who showed good performance in lane changing with no visual feedback. We defined the “non-naïve” participants as those who achieved a Return Ratio >= 0.5 in the no visual feedback condition. Note that the “non-naïve” participants did not have to make a conventionally accurate lane change (i.e. moving the vehicle precisely to the adjacent lane). They only demonstrated an intention to conduct a second, return phase in the no feedback condition.

Based on these criteria, 9 out of 31 participants were removed from further testing in Experiment 1. The remaining 22 “naïve” participants consisted of 13 males and 9 females, all at university ages (19 ~ 30), with driving experience of 3.90(M) ± 3.20 (SD) years. In Experiment 2, the same criteria resulted in 13 out of 41 participants being excluded from further testing. The remaining 28 “naïve” participants consisted of 19 females and 9 males, all at university ages (19 ~ 30), with driving experience of 5.79 (M) ± 4.82 (SD) years. All participants had normal or corrected to normal vision. Before starting the experiment, and during inter-trial breaks, participants were asked to select music to listen to. Music was played via a YAMAHA surround-sound system. Participants reported music helped them focus on the tasks and feel less bored during all 128 repeated lane changes. Each experiment usually took one hour to complete and participants were required to take at least a 2 minutes’ rest after each block to prevent the onset of motion sickness.

Results

The results of the two experiments are described here for the naïve participants. Data for the non-naïve participants appear in Appendix B.

Return Ratio

First, we analysed RR for all visual feedback conditions (“Road”, “Dark-Pre”, “Static”, “Dynamic”, “Dark-Post”) in Exp. 1 and (“Road”, “Dark-Pre”, “Static”, “Ground Plane”, “Dark-Post”) in Exp. 2 (see Figure 6a and Figure 6b, respectively). The results indicate that for both experiments, the highest RR appears in the “Road” condition and the lowest appears in “Dark-Pre”. RR for the other types of visual feedback lie between the two extremes. For Exp. 1 (Figure 6a), a repeated-measures ANOVA was carried out on RRs across visual feedback, suggesting that the effect of visual feedback was significant ($F(2.641,55.458) = 105.364$, $p < 0.001$, $\eta^2 = 0.834$). Further pairwise comparisons showed that RR for “Road” was the greatest by far ($p < 0.001$) while RR for “Dark-Pre” was the lowest. RR for “Dark-Pre” was lower than RR for “Static” ($p = 0.001$), RR for “Dynamic” ($p = 0.036$), and RR for “Dark-Post” ($p = 0.038$). It was also found that RR for “Static” was insignificantly larger than RR for “Dynamic” ($p = 0.066$). The results generally suggest that despite some minor improvements in RR over the fully naïve performance in darkness, participants failed to produce a sufficiently large second phase in the presence of optic flow.

ANOVA was again performed on Exp. 2 (Figure 6b), and yielded similar results. The effect of visual feedback was significant, $F(2.966,80.092) = 103.053$, $p < 0.001$, $\eta^2 = 0.792$. Further comparisons showed that RR for “Road” was again the greatest by far, $p < 0.001$. It was also discovered that RR for “Ground” was significantly larger than RR for “Dark-Pre” (p <

0.001), RR for “Static” (p = 0.023), and RR for “Dark-Post” (p < 0.001). RR for “Static” was also found to be significantly higher than RR for “Dark-Pre”, p = 0.023. Despite some improvements seen in flow fields, participants again failed to carry out a lane-change in the presence of flow information.

In order to investigate whether such low RR shown in the limited visual feedback (i.e. the condition other than full visual feedback) were consistent across trials (i.e. whether participants repeatedly generated this low RR across trials), we calculated the within-subject standard deviation (SD). The calculation of SD was based on the total number of trails participants conducted in any given visual feedback condition (e.g. “Static”). For example, participants conducted 16 trials in “Static”, so the SD for “Static” was calculated from those 16 trials. Thus, a small SD should reflect a consistent steering behaviour across trails. In Exp. 1, the SD for “Road” was 0.096(M) ± 0.012(SE), for “Dark-Pre” was 0.144(M) ± 0.023(SE), for “Static” was 0.167(M) ± 0.025(SE), for “Dynamic” was 0.174(M) ± 0.021(SE), for “Dark-Post” was 0.183(M) ± 0.028(SE). In Exp. 2, the SD for “Road” was 0.106(M) ± 0.007(SE), for “Dark-Pre” was 0.179(M) ± 0.029(SE), for “Static” was 0.181(M) ± 0.023(SE), for “Ground” was 0.256(M) ± 0.027(SE), for “Dark-Post” was 0.175(M) ± 0.023(SE). Clearly, those small SDs (around 0.2 in the flow fields) with the low RRs seen in the flow fields suggest that participants consistently omitted the return phase of a lane change across all trials. Taking “Ground” as an example, the mean RR was 0.513 and the mean within-subject SD was 0.256, hence a RR = 1 in “Ground” required 2 SD away from the mean (M(0.513) + 2*SD(2*0.256)). According to Chebyshev's theorem, an observation is rarely more than a few SD away from the mean. Let alone for “Dynamic” and “Static”, a RR = 1 would need about 3~4 SD away from the mean, which is very unlikely. Further, if we expect participants to conduct an excessive return phase (assuming they had the intention for a return phase but could not precisely estimate this phase), then the generated RR would be as much as 4~6 SD away from the mean. Thus, participants’ behaviour was consistent across trials. They did not attempt to change their steering behaviour for even few trials. In contrast, we calculated the SD in “Dark-Pre” for non-naïve participants (details can be seen in Appendix B).

In contrast, non-naïve participants showed a significantly greater variance in Return Ratios in “Dark-Pre”, i.e. they either oversteered or understeered, by a large margin. In “Dark-Pre”, the SD for non-naïve participants was twice as much as the SD for naïve participants. The fact that the non-naïve participants were not able to generate steady steering movements across trials indicates that they were merely attempting to conduct some form of bi-phasic manoeuvre (albeit inaccurately). It was not the case that they exhibited better spatial memory for this manoeuvre, for example. Therefore, the steering errors shown by non-naïve participants were large and random, whereas the steering errors for naïve participants were far more consistent ("accurately wrong" one might say). Details can be seen in Appendix B.

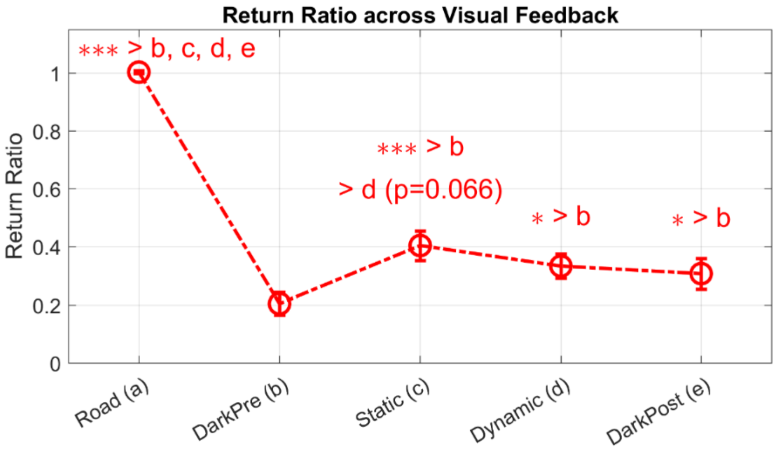

Figure 6a demonstrates RR for each type of visual feedback for Exp. 1. Error bars are SE. "" indicates 0.05 level; "***" indicates 0.001 level. Specially, RR for "Road" was 1.004 (M) ± 0.005 (SE), for "Dark-Pre" was 0.203 (M) ± 0.038 (SE), for "Statics" was 0.403 (M) ± 0.052 (SE), for "Dynamic" was 0.332 (M) ± 0.042 (SE), and for "Dark-Post" was 0.308 (M) ± 0.054 (SE).*

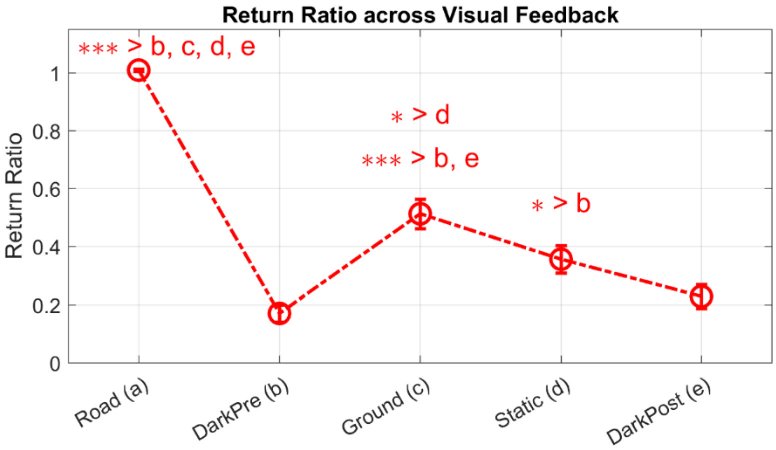

Figure 6b illustrates RR across all types of visual feedback for Exp. 2. Error bars are SE. "" indicates 0.05 level; "***" indicates 0.001 level. Specifically, RR for "Road" was 1.009 (M) ± 0.004 (SE), for "Dark-Pre" was 0.170 (M) ± 0.030 (SE), for "Ground" was 0.513 (M) ± 0.051 (SE), for "Static" was 0.356 (M) ± 0.048 (SE), and for "Dark-Post" was 0.228 (M) ± 0.041 (SE).*

RMSE

We then analysed participants' steering wheel profiles using RMSE, as described in the Analysis Section. The RMSE analysis was conducted in a way that a) Steering profiles in "Dark-Pre" were compared to those in "Road" (Road vs. Dark-Pre); b) Steering profiles in

“Static” were compared to those in “Road” (Static vs. Road) and those in “Dark-Pre” (Static vs. Dark-Pre); c) Steering profiles in “Dynamic” were compared to those in “Road” (Dynamic vs. Road) and those in “Dark-Pre” (Dynamic vs. Dark-Pre); d) Steering profiles in “Ground” were compared to those in “Road” (Ground vs. Road) and those in “Dark-Pre” (Ground vs. Dark-Pre); e) Steering profiles in “Dark-Post” were compared to those in “Road” (Dark-Post vs. Road) and those in “Dark-Pre” (Dark-Post vs. Dark-Pre). Figure 7a illustrates the results of RMSE analysis for Experiment 1, and Figure 7b the results from Experiment 2.

For Exp. 1, a repeated-measures ANOVA was conducted on “vs. Road” (red line in Figure 7a), revealing that the effect of visual feedback was significant ($F(2.018, 40.351) = 5.829$, $p = 0.006$, $\eta^2 = 0.226$). Further pairwise comparisons indicated that “Dark-Pre vs. Road” was significantly larger than “Dynamic vs. Road” ($p = 0.013$). It was also found that “Dark-Pre vs. Road” was insignificantly larger than “Static vs. Road” ($p=0.075$). A repeated ANOVA was also performed on “vs. Dark-Pre” (blue line in Figure 7a), suggesting that the effect of visual feedback was significant ($F(1.982,39.638) = 24.829$, $p < 0.001$, $\eta^2 = 0.554$). Further pairwise comparisons indicated that “Road vs. Dark-Pre” remained the largest. It was significantly larger than “Static vs. Dark-Pre” ($p = 0.003$), “Dynamic vs. Dark-Pre” ($p < 0.001$), and “Dark-Post vs. Dark-Pre” ($p < 0.001$). It was also found that “Static vs. Dark-Pre” was significantly higher than “Dynamic vs. Dark-Pre” ($p = 0.006$), and was insignificantly larger than “Dark-Post vs. Dark-Pre” ($p = 0.058$). In order to investigate whether the steering profiles in flow fields closer to those in “Road” or those in “Dark-Pre”, we performed a paired t-test on “‘Static vs. Road’ vs. ‘Static vs. Dark-Pre’, “‘Dynamic vs. Road’ vs. ‘Dynamic vs. Dark-Pre’”, and “‘Dark-Post vs. Road’ vs. ‘Dark-Post vs. Dark-Pre’” (Red vs. Blue in Figure 7a). The t-test suggests that a) “Static vs. Road” was insignificantly larger than “Static vs. Dark-Pre”, $t(21) = 1.905$, $p = 0.071$; b) “Dynamic vs. Road” was significantly larger than “Dynamic vs. Dark-Pre”, $t(21) = 3.387$, $p = 0.003$, effect size $d = 0.889$); c) “Dark-Post vs. Road” was also significantly larger than “Dark-Post vs. Dark-Pre”, $t(21) = 5.415$, $p < 0.001$, effect size $d = 1.286$. Taken together, the RMSE results suggest that steering wheel profiles in optic flow blocks and “Dark-Post” fit those in “Dark-Pre” significantly better. This implies that in flow fields, participants were simply replicating the “wrong” lane-changing manoeuvre. Nonetheless, some improvements could be found in flow fields since “Static vs. Road” < “Dark-Pre vs. Road” and “Dynamic vs. Road” < “Dark-Pre vs. Road”.

For Exp. 2 (Figure 7b), similar results were found. ANOVA conducted on “vs. Road” (red line in Figure 7b) revealed that the effect of visual feedback was significant, $F(2.182,56.733) = 24.846$, $p < 0.001$, $\eta^2.= 0.489$. Further pairwise comparisons showed “Dark-Pre vs. Road” was the largest one ($p < 0.001$), while “Ground vs. Road” was the smallest one ($p < 0.001$). A repeated ANOVA performed on “vs. Dark-Pre” (blue line in Figure 7b) showed that the effect of visual feedback was significant, F(3,78) = 43.832, $p < 0.001$, η^2.= 0.628. Further pairwise comparisons suggest that “Road vs. Dark-Pre” was the greatest, $p < 0.001$. It was also found that “Dark-Post vs. Dark-Pre” was significantly smaller than “Static vs. Dark-Pre” ($p < 0.001$) and “Ground vs. Dark-Pre” ($p < 0.001$). We also performed a paired t-test over “‘Ground vs. Dark-Pre’ vs. ‘Ground vs. Road’”, “‘Static vs. Dark-Pre’ vs. ‘Static vs. Road’”, and “‘Dark-Post vs. Dark-Pre’ vs. ‘Dark-Post’ vs. ‘Road’” (Red vs. Blue in Figure 7b). The t-test results revealed that a). “Static vs. Road” was significantly larger than “Static vs. Dark-Pre”, t(27) = 2.233, p = 0.034, effect size d = 0.566); b). “Dark-Post vs. Road” was significantly greater than “Dark-Post vs. Dark-Pre”, t(27) = 7.088, $p < 0.001$, effect size d = 1.849). Again, the RMSE analysis suggests that participants were not able to produce appropriate lane-change behaviour in flow fields and “Dark-Post”. Nonetheless, some improvements were also found in the presence of a flow field since “Ground vs. Road” < “Dark-Pre vs. Road” and “Static vs. Road” < “Dark-Pre vs. Road”.

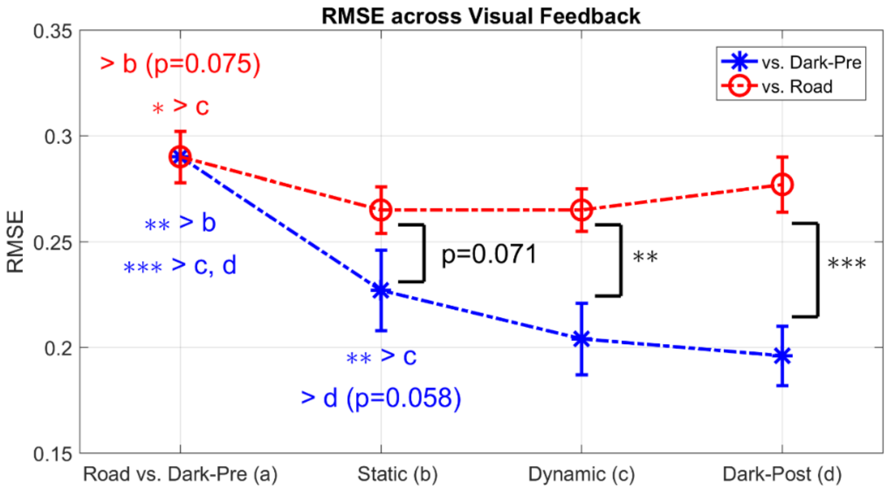

Figure 7a shows results from Exp 1 contrasting the RMSE fit for the drivers’ performance with full visual feedback (red line), vs that with no feedback (blue line). The size of the fit error (RMSE) between behaviour under normal feedback and the flow conditions is always larger than the fit error between the flow conditions and the behaviour seen without feedback – suggesting that flow was not sufficient to restore normal behaviour. Note that “Road vs. Dark-Pre” and “Dark-Pre vs. Road” (i.e. the cross point of red line and blue line) was obviously identical: 0.290 (M) ± 0.012 (SE). Error bars are SE. “” indicates 0.05 level; “**” indicates 0.01 level; “***” indicates 0.001 level. Specially, “Static vs. Road” was 0.265 (M) ± 0.011 (SE), “Dynamic vs. Road” was 0.265 (M) ± 0.010 (SE), “Dark-Post vs. Road” was 0.277 (M) ± 0.013 (SE); “Static vs. Dark-Pre” was 0.227 (M) ± 0.019 (SE), “Dynamics vs. Dark-Pre” was 0.204 (M) ± 0.017 (SE), “Dark-Post vs. Dark-Pre” was 0.196 (M) ± 0.014 (SE).*

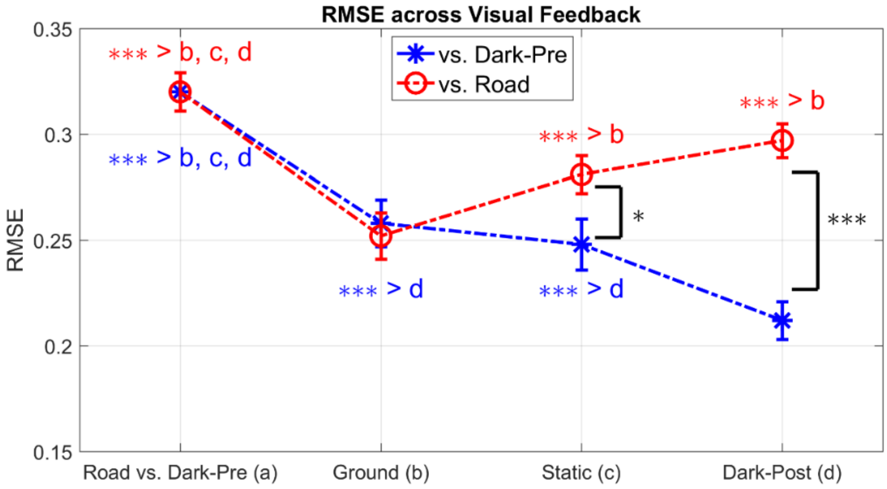

Figure 7b illustrates RMSE for Exp. 2. Error bars are SE. "" indicates 0.05 level, "***" indicates 0.001 level. Specially, "Ground vs. Road" was 0.252 (M) ± 0.009 (SE), "Static vs. Road" was 0.281 (M) ± 0.011 (SE), "Dark-Post vs. Road" was 0.297 (M) ± 0.008 (SE); "Ground vs. Dark-Pre" was 0.258 (M) ± 0.012 (SE), "Static vs. Dark-Pre" was 0.258 (M) ± 0.012 (SE), "Dark-Post vs. Dark-Pre" was 0.212 (M) ± 0.009 (SE). Note that "Road vs. Dark-Pre" and "Dark-Pre vs. Road" (i.e. the cross point of red line and blue line) was obviously identical (0.320 (M) ± 0.009 (SE)).*

Summary of Results

The RR results clearly indicate that only in the presence of full visual feedback could participants complete a balanced, bi-phasic manoeuvre. In all the other visual feedback conditions, participants showed a RR significantly lower than 1.0, most of the time the RR did not even reach 0.5 --- the value we used to screen non-naïve participants in the no visual feedback condition. We believe the low RR was mainly due to a lack of intention to conduct a return phase steering movement. If participants had the intention to conduct a return phase, then they should have demonstrated a RR > 1 in at least some trials and RR < 1 in others. Instead, they consistently produced return ratios well below 1, as can be seen from the low within-subject SD. The small standard errors (SE) seen in Figure 6a and 8b also suggest that this finding was consistent across as well as within participants. Further, the comparison between within-subject SD for "naïve" participants and that for "non-naïve" participants indicate the low RR was not related to spatial memory – see also Appendix B. As to the RMSE analysis, we aimed to directly compare steering profiles (i.e. how participants steered the vehicle) under different visual feedback conditions. Despite some minor improvements seen in the optic flow blocks (since "Static vs. Road" < "Dark-Pre vs. Road" and "Ground vs. Road" < "Dark-Pre vs. Road"), it is clear from the figures (red lines and blue lines in Figure 7a and 9b) that steering profiles in flow fields were generally closer to those in “Dark-Pre”. This indicates that given the cues provided in optic flow, participants could not replicate a “correct” lane change (i.e. a bi-phasic manoeuvre). On the contrary, they produced behaviour in optic flow that most closely resembled that seen in the absence of visual feedback. An interesting finding is that steering profiles in the ground plane condition were split between the no feedback and full feedback conditions, while steering profiles in static flow and dynamic flow were both closer to those in the no feedback condition. These data appear to imply that cues provided by a ground plane (i.e. locomotor flow lines, integrable trajectories, etc.) were of some use to participants.

One issue which may be impacting our drivers’ behaviour in the flow conditions is the previously reported bias participants show to point towards the centre of the screen (Van den Berg 1996, Cutting, Vishton et al. 1997, Ehrlich, Beck et al. 1998). It is perhaps conceivable that this bias affects the willingness of drivers to steer away from the centre during the second phase of the movement. Perhaps, but we note that this effect is relatively modest (see (Saunders 2014)). The low RR values achieved by our participants (barely half the required amplitude) suggest that a simple bias of this kind cannot explain the entire effect seen in our study. We likewise do not believe that the results are due to a failure of memory. If a requirement to do the task in darkness or flow is a better spatial memory, one might expect our non-naïve participants to do a better job of lane changing than our naïve participants. This was not the case. The non-naive participants produced much larger ranges of RR than our naïve participants and almost invariably failed to keep the vehicle on the road – see Appendix B. Another concern might be that in the full cue condition, participants had the vanishing point (i.e. the convergence of lane lines) as a target to steer toward, while in other conditions such a target did not exist. Some might be worried that the failure of lane change in optic flow was not due to the inability to use flow information but the inability to identify whether the location is a straight path following a lane change because of the lack of a target. Indeed, a target is a reference object providing information as to whether the observer is travelling to the left or right of the object. In that case, one can use visual direction and target drifting to change lanes. For example, if one steers towards right then the target drifts to left, then this person steers back to cancel such drift (because he / she knows target drifting means he / she is not going straight towards the target). In this case, a lane change can be conducted even with a target alone, although optic flow is likely to improve the performance. As a result, assuming drivers can change lane properly in an environment with flow field and a target, it would be difficult to argue whether it is because of optic flow or the target or both. It is also a fact that lane change naturally does not require a target. A similar lane related study (lane keeping) conducted by Kountouriotis et al. found that gaze was mainly directed towards the visible lane rather than a point far away (e.g. the vanishing point) (Kountouriotis, Floyd et al. 2012).

Discussion

Our finding is generally consistent with various previous studies. Firstly, the improvements of steering profiles along with higher RR in flow fields are consistent with studies reporting that the addition of flow assists heading control (Li and Warren 2002, Wilkie and Wann 2002, Wilkie and Wann 2003, Li, Stone et al. 2011, Li and Cheng 2011a, Kountouriotis and Wilkie 2013, Li and Cheng 2013, Li and Niehorster 2014). Secondly, our results are in line with Kountouriotis and Wilkie (2013) who showed that, despite perceiving heading accurately, participants can sometimes produce poor performance in a steering-towards-a-target tasks. An interesting question which emerges from our work is why heading estimation was accurate in the flow conditions, but lane change performance was so poor. The answer may be related to the cues drivers use. Heading estimation is undoubtedly an important cue but we should not always take it as a sufficient cue just because its accuracy is high. Here we consider other popular steering models that do not heavily rely on heading estimation.

The future path (FP) strategy proposed by Wann, Land, and colleagues emphasizes the contribution of visual direction towards a fixation 1~2 seconds ahead during self-motion (Wann and Land 2000, Wann and Swapp 2000, Wilkie and Wann 2006, Wilkie, Wann et al. 2008). In theory, it is possible for drivers to continuously switch fixations to make a lane change, e.g. gradually switch fixation from the current lane to the destination lane, as vehicle continuously approaching fixations eventually a lane change is conducted. Alternatively, Salvucci and Gray (2004) developed a two-point steering strategy on the basis of previous work (Donges 1978, Land and Horwood 1995). In their model a lane change can be treated as approaching a destination lane by switching the near and far points from the current lane to the destination lane. As a consequence, a lane change can be carried out by using visual direction to near and far points. Salvucci et al. showed the simulated lane changing results based on this model are very similar to the results generated by human participants (Salvucci and Liu 2002). Indeed, some recent studies show support for the two-point steering strategy (Frissen and Mars 2014, Lehtonen, Lappi et al. 2014). That said, Cloete and Wallis (2011) report that the results from one influential study (Land and Horwood 1995) were heavily influenced by the very low refresh rate employed suggesting that evidence for this model should be re-evaluated.

Li and Chen studied the contribution of optic flow, bearing angle, and splay angle in lane keeping (Li and Chen 2010). Their results show that splay angle was generally sufficient to keep lane position during random lateral perturbations, but that added optic flow improved overall performance. Robertshaw, Kountouriotis, and colleagues reported that steering control on a road is achieved by integrating optic flow, road edges, and gaze direction (Robertshaw and Wilkie 2008, Kountouriotis, Floyd et al. 2012, Kountouriotis, Shire et al. 2013). In their experiments, participants showed large steering errors (i.e. they were unable to maintain required position in lane) when road edge information was weak (i.e. removed or faded road edges). Interestingly, those steering strategies all require, or at least mention, the use of fixations. FP and the “two-point” strategy require visual direction to one or two fixations, whereas Li et al.’s proposal needs to use fixation to measure the splay angle. Robertshaw et al.’s finding also suggests that drivers generally direct gaze toward the visible lane. Taken together, we propose that for steering tasks, fixations may be important. This would explain why participants failed in the flow fields consisting of clouds of dots, since there was no obvious target upon which to fixate. However, the fact that participants also failed in our ground plane task appears at odds with this idea, since the ground plane was able to provide fixation targets. One explanation for this is that the ground plane used in our (and many other) studies, lacks outstanding features for drivers to fixate and track. In this case, even though participants fixated a feature for a few seconds they might soon lose it due to the isotropy of the filtered texture. This may explain why there was at least a small improvement in performance in the ground plane condition over flow alone. As a useful steering strategy, fixations not only provide visual direction, splay angle, etc., but also make path integration possible (e.g. locomotor flow lines, trajectories).

Conclusion

Overall, the results reported here suggest that participants are unable to complete a lane change in the presence of optic flow alone. Instead our participants’ steering movements in optic flow most closely resembled those seen in the absence of visual feedback. It appears, therefore, that an ability to perceive heading accurately does not result in an ability to carry out the type of bi-phasic steering-wheel movement required in tasks typified by a lane-change.

In light of the moderate improvements seen in the presence of a ground plane, we would tend to agree with many other authors that that gaze towards targets within the environment play a decisive role in everyday driving activities. Hence we would argue that future studies should investigate the “future-path” and “two-point” models. Future work, perhaps focused on eye movement recording, will be required to further dissociate these possibilities. Note that this does not deny flow some role in steering. The presence of optic flow would likely improve overall performance, if only because it provides important cues to forward velocity and overall heading, our work merely excludes it as the primary driver of steering behaviour in humans.

Appendix A Heading Perception Experiment

Method

Three optic flow fields were tested in this experiment, with two versions of static optic flow and a ground plane. The reason why we used two versions of static optic flow was that: i). we replicated the static optic flow used in lane change experiment (which had a depth range of 1000 meters); ii). we also used a popular design of static optic flow (which had a depth range of 30 meters, we use the term “shallow static flow” to refer to this version of static optic flow). To our best knowledge, we did not find any other lab testing static flow at a depth range of 1000 meters. Hence, we added the shallow optic flow for comparing to the static flow we used. The experimental design mimicked the study of Warren et al. (Warren, Morris et al. 1988) and Foulkes et al. (Foulkes, Rushton et al. 2013). At the beginning of each trial, a red dot appeared with radius of 0.1^o at various locations along the horizon ($\pm 2^o$, $\pm 4^o$, relative to the center of the screen) and participants were instructed to fixate on the red dot. One second later, while participants maintained fixation, the flow field was presented for 2s. During the 2s presentation, optic flow moved in a radial pattern consistent with forwards translation of the participant at a speed of 70 km/h. The direction of the translation (FoE) offset relative to the red dot was ($\pm 0.2^o$, $\pm 0.5^o$, $\pm 1^o$, $\pm 2^o$, $\pm 4^o$). After optic flow was removed, participants had to indicate whether they were travelling to the left or right of the red dot by pressing the left or right arrow key on a keyboard.

The three flow fields were tested in three separate blocks, presented in counter-balanced order across participants. For each block, there were 4 (red dot locations: $\pm 2^o$, $\pm 4^o$) × 10 (FoE offset: $\pm 0.2^o$, $\pm 0.5^o$, $\pm 1^o$, $\pm 2^o$, $\pm 4^o$) × 4 repetitions = 160 trials. For analysis, the data was collapsed over the negative and positive (left and right) FoE offsets and then over red dot locations, resulting in 32 repetitions for each of 5 FoE offsets (0.2^o, 0.5^o, 1^o, 2^o, 4^o). In total, there were 3 (blocks) × 160 (trials per block) = 480 trials.

Stimulus

The three flow fields used in the heading perception experiment are illustrated in Figure 1a (Left, “shallow optic flow”), Figure 1a (Right, “static optic flow”), and Figure 1b (ground plane). The shallow optic flow (Figure 1a, Left) was the same as the static optic flow, except it had a depth of 30 meters instead of 1000 meters. For shallow optic flow, there were 12,000 white dots randomly distributed across space, with around 2000 dots visible in any one frame. The static optic flow (Figure 1a, Right) consisted of 80,000 white dots. Those 80,000 dots were randomly distributed across space, with around 11,000 dots visible in any one frame. Dots had radii of 3mm (4X anti-aliasing), approximately 0.05o in visual angle. The ground plane (Figure 1b) consisted of a Gaussian-filtered texture. We only tested heading perception for simple radial flow fields. This is because we were only interested in examining whether our stimulus was sufficient for participants to perceive heading accurately. We did not involve other factors (i.e. path rotation, eye rotation, simulated eye rotation, etc.) to avoid introducing unnecessarily complication to the experimental design.

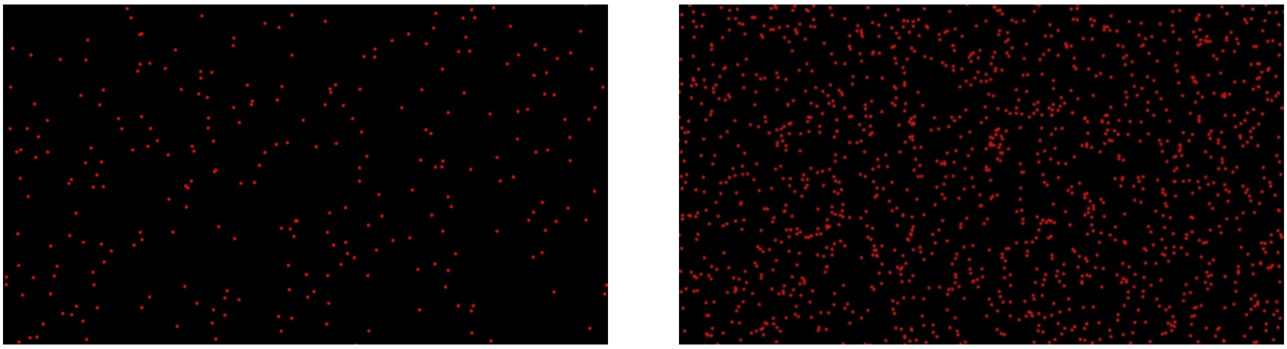

Figure 1a demonstrates the shallow optic flow (left) and static optic flow (right). For clarity, all dots have been magnified and rendered in red.

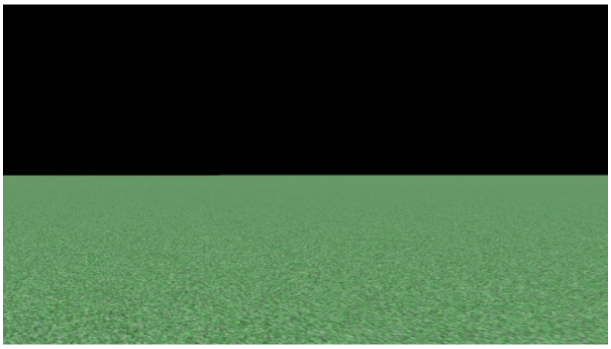

Figure 1b presents the textures in the ground plane.

Participants

For the heading perception experiment, 21 students (7 female + 14 male) were recruited. All participants were at university ages (18 ~ 28) and had normal or corrected-to-normal vision. One female participant reported symptoms of nausea while being exposed to the shallow optic flow and so did not complete the experiment. All participants were given around fifteen minutes (five minutes per block × three blocks) practice. It usually took 2 hours for participants to complete the heading perception experiment.

Analysis

Analysis was similar to that of Warren et al. (Warren, Morris et al. 1988) and Foulkes et al. (Foulkes, Rushton et al. 2013). For each of the three blocks, cumulative Gaussian psychometric functions were used to fit participant's responses (% correct) vs. FoE offsets. Thresholds were defined as the FoE offset for which participants hit the 75% correct level. For ANOVA, Greenhouse-Geisser was used to correct a violation of sphericity if necessary and Sidak was used to correct pairwise comparisons.

Results

Thresholds for the three optic flow fields are shown in Figure 2. The magnitude of the thresholds is consistent with those in previous papers (e.g. (Warren, Morris et al. 1988), (Foulkes, Rushton et al. 2013)). The threshold for shallow optic flow was 0.550 (M) ± 0.073 (SE); for static optic flow was 1.284 (M) ± 0.205 (SE); and for the ground plane was 1.240 (M) ± 0.194 (SE). A repeated ANOVA was performed on thresholds across three optic flow blocks, suggesting that the effect of block was significant (F(1.466, 27.860) = 6.024, p = 0.012, η2 = 0.241). Further pairwise comparisons indicated that the threshold for shallow optic flow was significantly smaller than the threshold for static optic flow (p = 0.003), and was also significantly smaller than the threshold for the ground plane (p = 0.012).

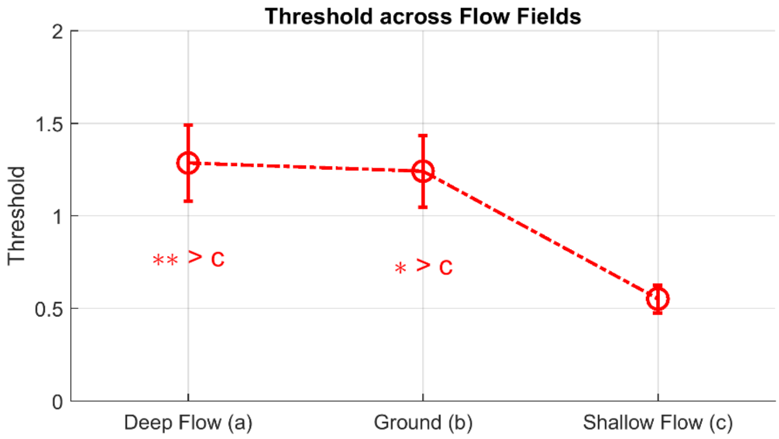

Figure 2 demonstrates the average thresholds over participants for three optic flow environments. '' indicates 0.05 level. '**' indicates 0.01 level. Error bars are SE.*

Performance of heading perception was best in the shallow optic flow condition, most likely because the shallow optic flow provided the most noticeable FoE. In shallow optic flow, the furthest dots were only 30 meters ahead of the observer, while those in deep optic flow were 1000 meters away. Due to the characteristic of perspective, many of the dots in the deep optic flow were effectively stationary and did not provide much motion information. As a consequence, participants felt as if they were travelling faster in shallow optic flow than they were in static optic flow. Despite this difference, participants perceived heading accurately across all three flow fields. These thresholds were well with the range necessary for humans to control self-locomotion (Cutting 1986). We conclude that the static optic flow and ground plane stimuli were sufficient for accurate heading perception during self-locomotion.

Appendix B Results for non-naïve participants in no visual feedback condition in Exp. 1 & 2

Return Ratios (RR) for all participants in the no visual feedback condition (“Dark-Pre”) in experiments 1 and 2 are shown in Figure 1a and Figure 1b, respectively.

As a supplement to RR, we analyzed the within-subject standard deviation (SD) for both non-naïve participants and naïve participants in the no visual feedback condition only. The calculation of within-subject SD was described in Return Ratio section in the main body. In Exp. 1, the SD for non-naïve participants in “Dark-Pre” was 0.310(M) ± 0.053(SE), whereas the SD for naïve participants in “Dark-Pre” was 0.144(M) ± 0.023(SE). An independent t-test revealed that SD for non-naïve participants was significantly higher than SD for naïve participants, t(29) = 3.406, p = 0.002, effect size d = 1.348. In Exp. 2, the SD for non-naïve participants in “Dark-Pre” was 0.300(M) ± 0.03(SE), whereas the SD for naïve participants in “Dark-Pre” was 0.179(M) ± 0.029(SE). An independent t-test revealed that SD for non-naïve participants was significantly higher than SD for naïve participants, t(39) = 2.585, p = 0.014, effect size d = 0.868. Overall, the results suggest that compared to naïve participants’ steering movements, non-naïve participants showed a greater variance in steering movements across trials. This means that non-naïve participants could not maintain a steady steering profiles in different trials, whereas naïve participants were able to. Figure 2 shows three non-naïve participants’ (from Exp. 1 and 2) RR across trials in “Dark-Pre” and three naïve participants’ (from Exp. 1 and 2) RR across trials in “Dark-Pre”. It is clear from the figure that non-naïve participants’ steering movements fluctuated considerably, whereas naïve participants’ steering movements are reasonably steady. Those non-naïve participants never maintained RR close to 1, rather they oversteered and understeered frequently around RR = 1. Some of them also demonstrated an overall tendency to oversteer (e.g. the green line of Figure 2). Therefore, the non-naïve participants’ lane change performance in “Dark-Pre” cannot be explained by a better spatial memory but by an attempt to conduct a bi-phasic manoeuvre. On the other hand, we further checked whether non-naïve participants precisely moved the vehicle precisely to the adjacent lane. For short, the answer is no. Because in our program there was an algorithm for collision detection, we can easily know whether the vehicle went off road or not. The collision detection was implemented in such way that if the vehicle went beyond the road edge (see Figure3b(Right) in the main body), the program would simply write a value to a text file. The road edge was invisible in the no visual feedback condition or optic flow, and the collision detection merely recorded steering without impeding the vehicle’s progress in any way. The results indicate all non-naïve participants went off road in 94% of the total trials in “Dark-Pre”. This was because the participants could neither estimate the appropriate steering amplitude in the no visual feedback or optic flow, nor could they estimate the proper duration of a steering phase. Thus, even though sometimes they conducted an almost perfect bi-phasic manoeuvre, they still went off road due to their selecting an inappropriate duration of steering movements or incorrect steering amplitude. Again, it is important to be aware that we did not check whether a conventionally correct lane change was conducted or not, our analysis focusses on the question of whether our participants were attempting to produce bi-phasic steering movements or not. It should be clear now that non-naïve participants also performed poorly in moving the vehicle accurately. However, they did demonstrate a strong intention to conduct a bi-phasic manoeuvre.

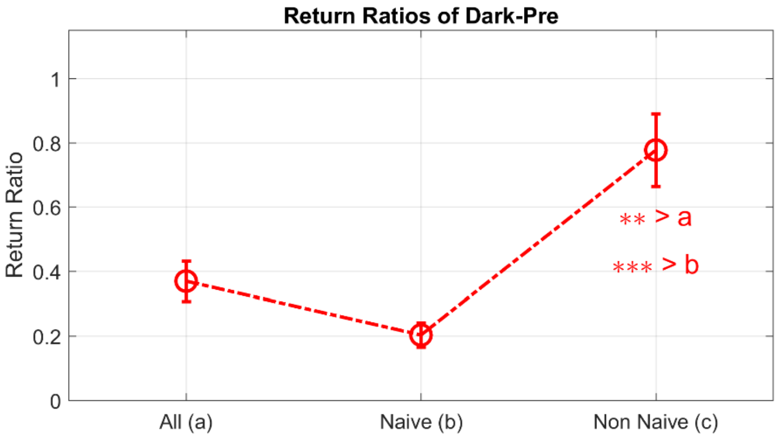

Figure 1a shows Return Ratios for all participants, naïve participants, and non-naïve participants in Exp. 1. Specially, RR in ‘’Dark-Pre” for all participants was 0.370 (M) ± 0.063 (SE), and that for naïve was 0.204 (M) ± 0.039 (SE). In contrast, non-naïve participants showed a RR of 0.777 (M) ± 0.113 (SE). A one-way Anova revealed that the effect of groups (all, naïve, and non-naïve) was significant, $F(2, 59) = 11.812$, $p < 0.001$, $\eta^2 = 0.286$. *Results of pairwise comparison is shown on the graph. “**” indicates 0.01 level. “***” indicates 0.001 level.*

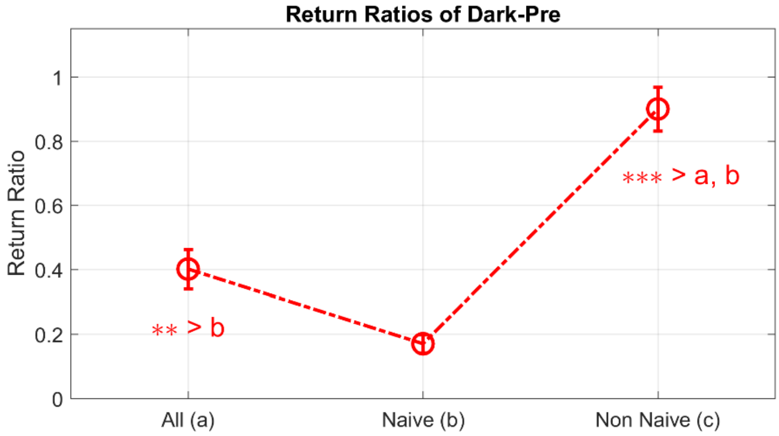

Figure 1b shows Return Ratios for all participants, naïve participants, and non-naïve participants in Exp. 2. Specially, RR for all participants in "Dark-Pre" was 0.401 (M) ± 0.043 (SE), and that for naïve was 0.170 (M) ± 0.030 (SE). Nonetheless, RR for non-naïve participants was 0.900 (M) ± 0.068 (SE). A one-way Anova revealed that the effect of group (all, naïve, non-naive) was significant, F(2, 79) = 25.028, p < 0.001, $\eta^2 = 0.388$*. Results of pairwise comparison is shown on the graph. "**" indicates 0.01 level. "***" indicates 0.001 level.*

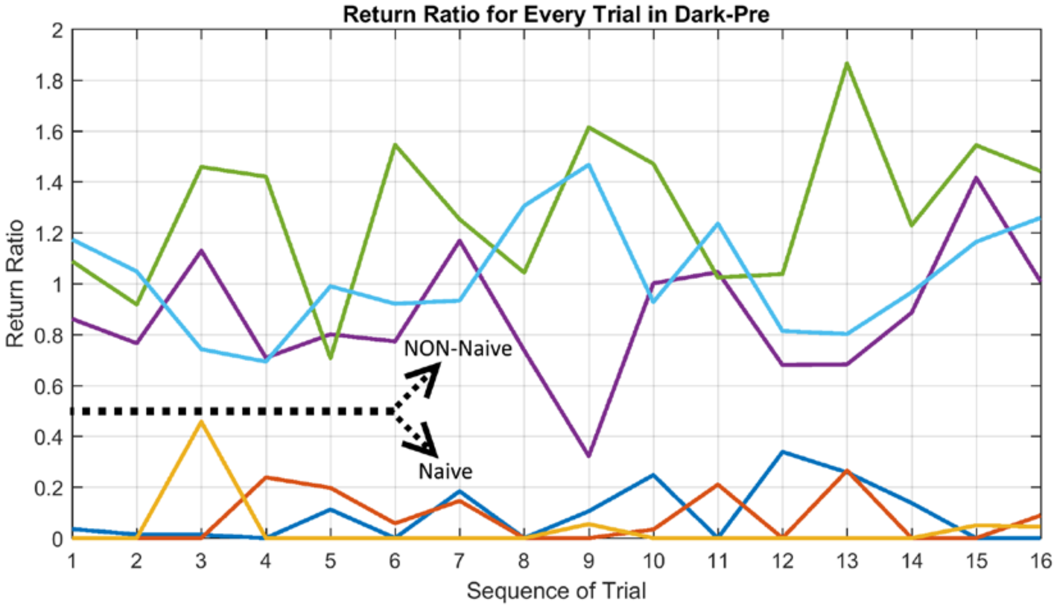

Figure 2 shows Return Ratio for every trial in "Dark-Pre" for both non-naïve and naïve participants.

Appendix C Techniques of RMSE analysis

It is possible to complete a lane change successfully with quite different steering profiles. A driver may start initiating a lane-change at different time points and activating a returning phase with unpredictable delays for example. Therefore, to best fit their behaviors with their own baselines, a time shift and a correction is essential, for time-shift see Figure 1 and for correction see Figure 2 and Figure 3.

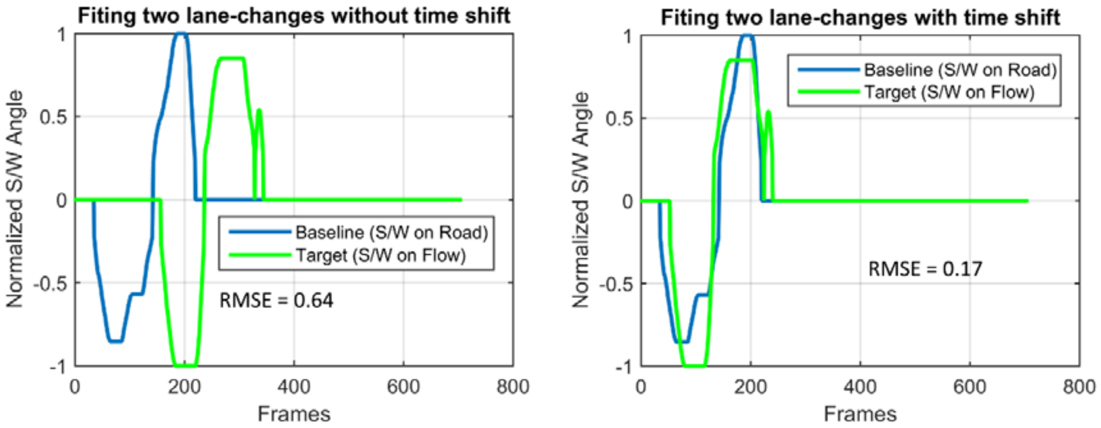

Figure 1 shows that the original fit gives a large RMSE (0.64) but a time-shift version gives a small RMSE (0.17). In this case, the time shift is about 2s (105 frames).

As shown in Figure 1, the same person conducted two lane-changes (both show a bi-phasic-like manoeuvre) but at different times. Hence a time-shift is essential in order to compare a subject's behavior in the two trials. In this case, if no time shift is introduced then a RMSE produced by this bi-phase vs. bi-phase fitting will be indistinguishable from a uni-phase vs bi-phase fitting (because both result in a large RMSE). A range of 4s time-shift was allowed in the current RMSE analysis, which means an algorithm was written to shift the target from -4s (negative number means backwards) to 4s (positive number means forwards) and pick up the best fitting results (by selecting the minimal RMSE).

In addition, before any comparison, a correction was conducted to each steering profile, which is described in Figure 2 and Figure 3. As can be seen from both figures, the corrected version aligns the effective phases of each steering wheel profile so it only compares the phases that subjects actively produced. Use of an uncorrected profile would not reflect our subjects' real intention. We were interested in whether he/she conducted a bi-phasic manoeuvre or uni-phasic manoeuvre (subjects' intention), rather than the precise temporal characteristics he/she employed. Figure 2 shows clearly that the uncorrected version of analysis generates a large RMSE, despite both manoeuvres being bi-phasic. Because correction only compares effective phases produced by subjects, it doesn't affect a uni-phase vs. bi-phase RMSE (see Figure 3).

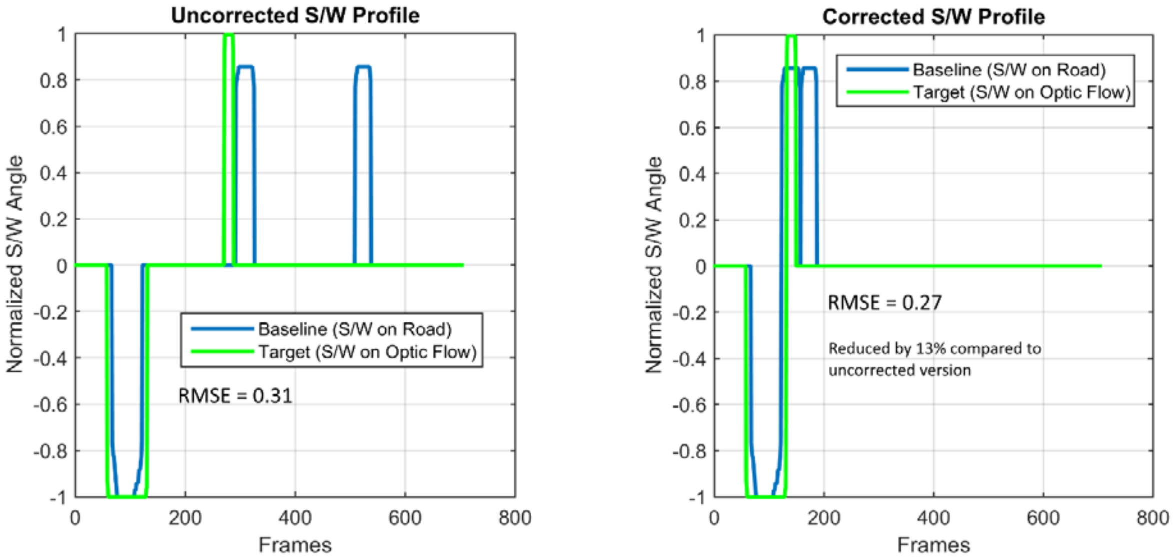

Figure 2 shows comparing two Steering Wheel Profiles with uncorrected method (Left) and corrected method (Right).

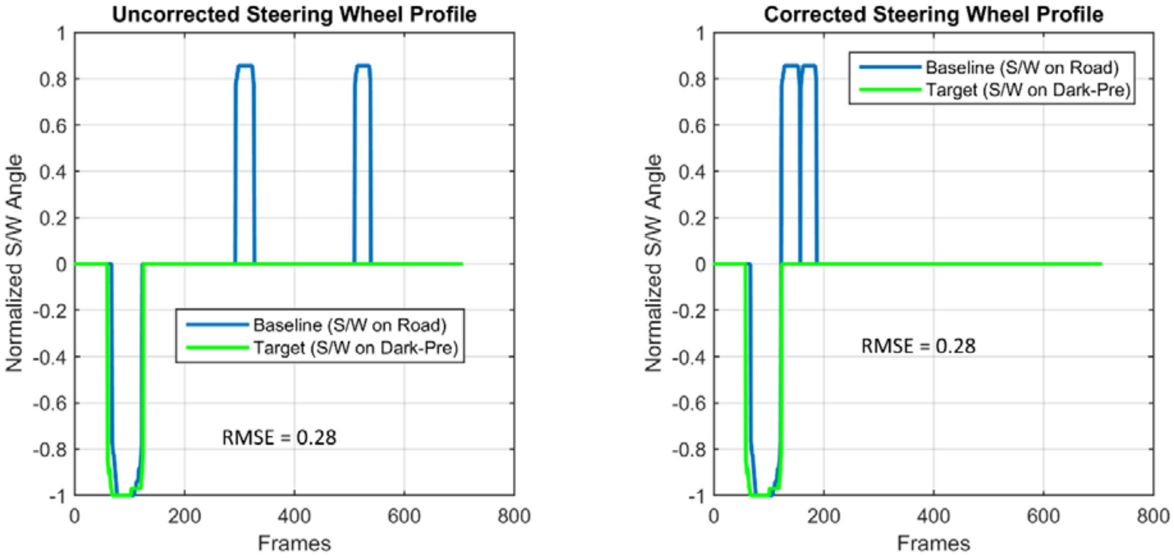

Figure 3 shows that because correction only compares effective phases produced by subjects, it doesn't affect a uni-phase vs. bi-phase RMSE. In addition, the RMSE of Figure 3 (Left, uni-phase vs. bi-phase, uncorrected) is even smaller than the RMSE of Figure 2 (Left, bi-phase vs. bi-phase, uncorrected), suggesting an uncorrected version is inappropriate because it doesn't reflect the difference of our subjects' true behavior.

Chapter Four - Study 3: A Test of Parallel-Parking

Experiment Parallel Parking Using Oculus Rift DK2 (A Pilot Experiment)

Introduction

So far, this thesis has focused on lane-changing and related work. Another everyday driving task sharing a similar characteristic to lane-changing is parallel parking. Parallel-parking requires a bi-phasic steering movement whilst moving backwards, while lane-changing usually requires a bi-phasic steering movement when driving the vehicle forwards (Figure 1a). One might wonder whether drivers display similar systematic errors (i.e. uni-phasic instead of bi-phasic responding) during parallel parking with no visual feedback (i.e. Figure 1b). We conducted an experiment to examine this.

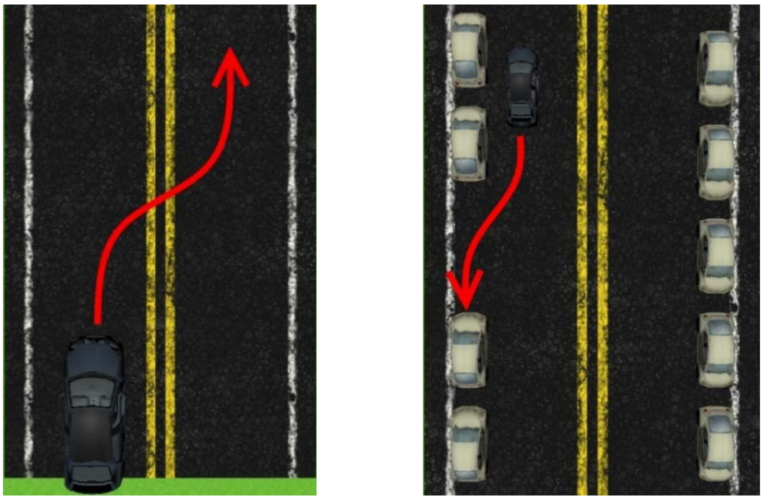

Figure 1a shows a correct lane-change (Left) and a correct parallel-parking (Right).

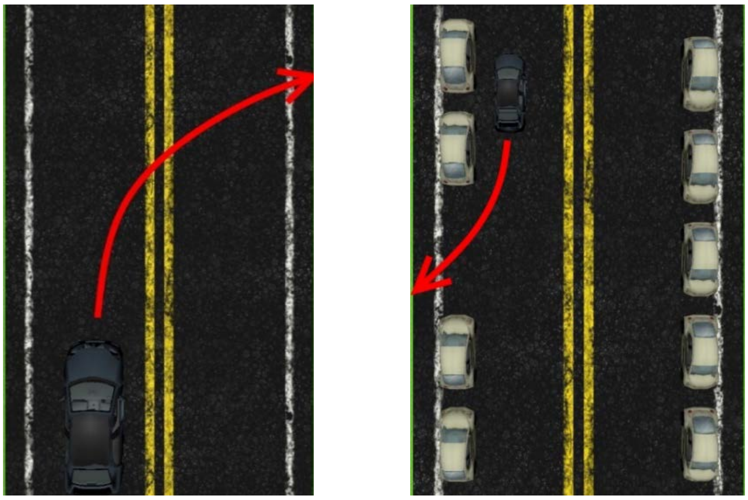

Figure 1b shows a wrong lane-changing manoeuvre (no return phase) and a wrong parallel-parking manoeuvre (no return phase).

As shown in Figure 1a, generally lane-change and parallel parking share the same steering movement but in the opposite direction. It has been shown in previous studies that without visual feedback drivers make systematic errors during lane changing (i.e. no/little Return Phase, see Figure 1b (Left)). But will drivers show the same mistake in a different manoeuvre that nonetheless requires very simliar steering movements? One might expect drivers to reproduce the systematic errors seen in lane changing, in parallel-parking too (i.e. Figure 1b (Right)). However, it is possible that drivers treat the two manoeuvres differently. Parallel parking requires the driver to turn around and look backwards or look at the back-mirror. Either way, it needs special visuomotor mapping to figure out correct steering movements. By contrast, for lane change a natural visuomotor mapping would suffice since it only needs driver to look ahead naturally for most of the time. As a result, drivers may spend extra focus on practising parallel-parking to establish such unusally mapping. It is not surprising that drivers may have internalized a more comprehensive model for parallel-parking. Lane-changing, on the other hand, can be condcuted without any special concern about viusmotor mapping, and as a result drivers may ignore the underlying mechanism (i.e. the bi-phasic characteristic of lane change manoeuvre). Taken together, there is a chance that drivers may have developed different internal models for to these two manoeuvres despite their fundamental similarity.

Method

The latest Virtual Reality (VR) technology was used to implement this experiment. The author wrote a program in C++ using the OpenSceneGraph library and Oculus SDK for this experiment, as described in Chapter 1. An Oculus Rift Dk2 running at 75Hz was used to render the scene. The Oculus Rift DK2 provided a field of visual about 110º (horizontal) × 95º (vertical). The resolution was 960 × 1080 per eye. A laptop with an i7 CPU, 16GB Ram, and a GTX 680 graphic card was used to run the program at 75 frames per second. The reason why we used an Oculus Rift Dk2 is that a VR Head Mount Display (HMD) conveniently gives observers the ability to actually look backwards during parallel parking. In this experiment, the function of rear view mirror was not implemented, and as a result one needs turn his/her head and look backwards to park the vehicle. Figure 2 shows an example of the virtual environment built in Oculus Rift DK2.

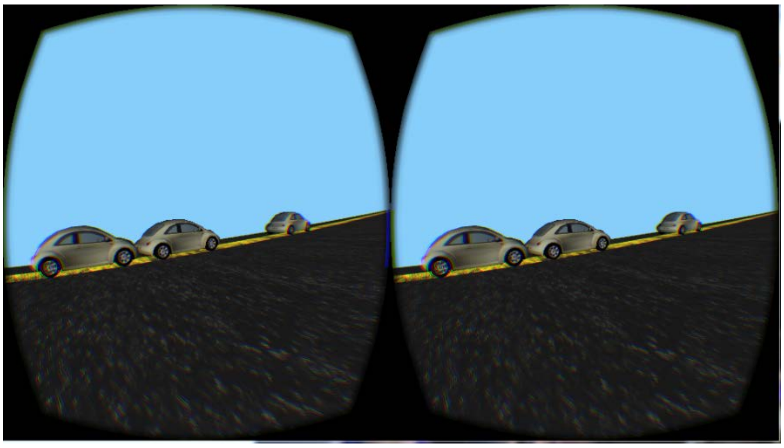

Figure 2 shows the virtual environment of this experiment.

Procedure

There were 4 blocks in this experiment. Block 1 and Block 4 were always the usual lane-changing task. Block 1 was designed to examine whether participants were naive or non-naive. Naive participants were those who showed the systematic error during lane-changing with no visual feedback (i.e. Figure 1b (Left)), while non-naive participants were those who demonstrated reasonably good performance in lane changing with no visual feedback (i.e. Figure 1a (Left)). Block 4 was designed to examine whether participants changed their behaviour after exposure to parallel parking tasks. Block 2 and Block 3 were parallel parking and reverse lane-changing (i.e. changing lane when driving backwards) in a counter-balanced order between participants. As mentioned above, parallel parking shares some basic characteristics with lane changing, except, and this may be important, it is conducted with the vehicle moving in reverse. We therefore added a reverse lane-changing block so that we can compare participants' steering behaviour among usual lane-changing, reverse lane-changing, and parallel parking.

There were 10 trials in each block. In lane-changing blocks, participants conducted two lane-changes in each trial (first lane change with full visual feedback + last lane change with no visual feedback). In the parallel parking block, participants conducted two parallel-parking manoeuvres in each trial (first parallel-parking with full visual feedback + last parallel parking with no visual feedback). Because participants had to park the vehicle twice in each trial, the vehicle was reset to its original position as soon as participants finished the first parking manoeuvre so that they could re-park later. 12 seconds were given to participants to complete the lane-changing manoeuvre. 30 seconds were given to participants to complete the parallel-parking task. In this experiment, the simulated vehicle always ran at 8 km/h across all blocks since this is a typical speed during parallel-parking in the real world. We also had to limit the simulated vehicle's speed because we found the majority of participants experienced serious motion sickness if vehicle was running at a daily speed from 30 km/h to 60km/h.

Participants

9 participants were recruited. All participants were at university ages from 19 to 22. They all had normal or corrected-to-normal vision. They all had at least two-year driving experience. All participants were given time to practise under normal visual feedback before running the actual experiment.

Analysis

Return Ratio (RR for short, see Figure 3 for definition, see also (Macuga, Beall et al. 2007, Wallis, Chatziastros et al. 2007)) was used to measure whether a participant conducted a lane change / parallel parking successfully. RR is a convenient metric for quantifying the return phase of a bi-phasic manoeuvre. RR is defined as the ratio of the heading change seen during the return (second) steering movement, divided by the heading change seen during the outward (first) steering movement. If H_{peak} denotes the peak value of heading, and H_{final} the final value of heading, we have

$$\text{RR} = \frac{H_{peak} - H_{final}}{H_{peak}}$$

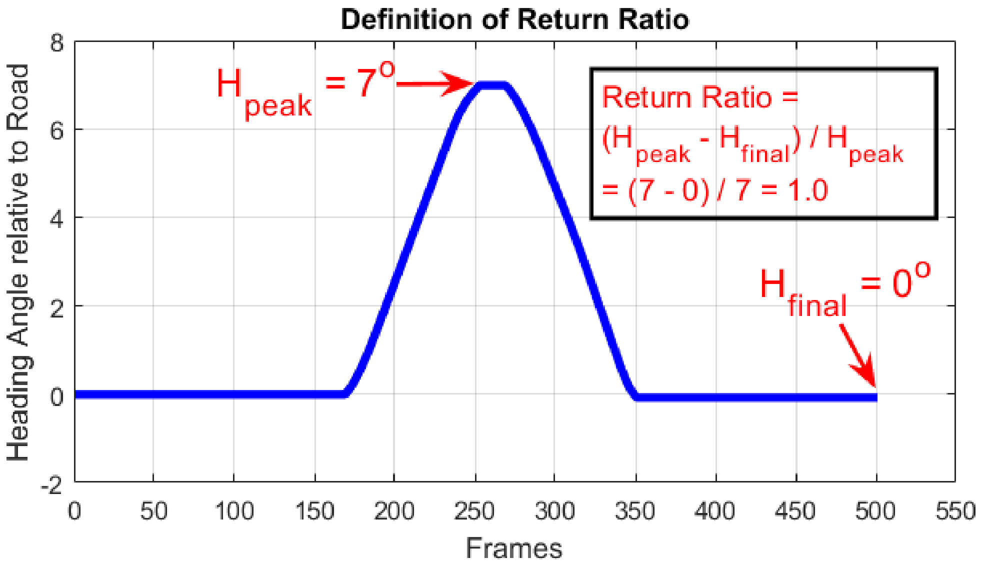

Figure 3 Heading changes for one subject during a lane-change with full visual feedback. The Return Ratio (RR for short), is defined as $(H_{Peak} – H_{Final}) / H_{Peak}$.

Obviously, a RR close to 1 indicates an almost perfect bi-phasic manoeuvre (as is Figure 3 and Figure 1a), while RR close to 0 indicates a uni-phasic manoeuvre with no return phase (as is Figure 1b). In addition to RR, we also analysed duration of each steering phase (for details see Results section). The duration of each steering phase is defined in Figure 4. The duration of the first steering phase is calculated from the onset of the manoeuvre to the moment at which heading reaches its peak. The duration of the second steering phase is calculated from the end of the first steering phase to the end of the manoeuvre.

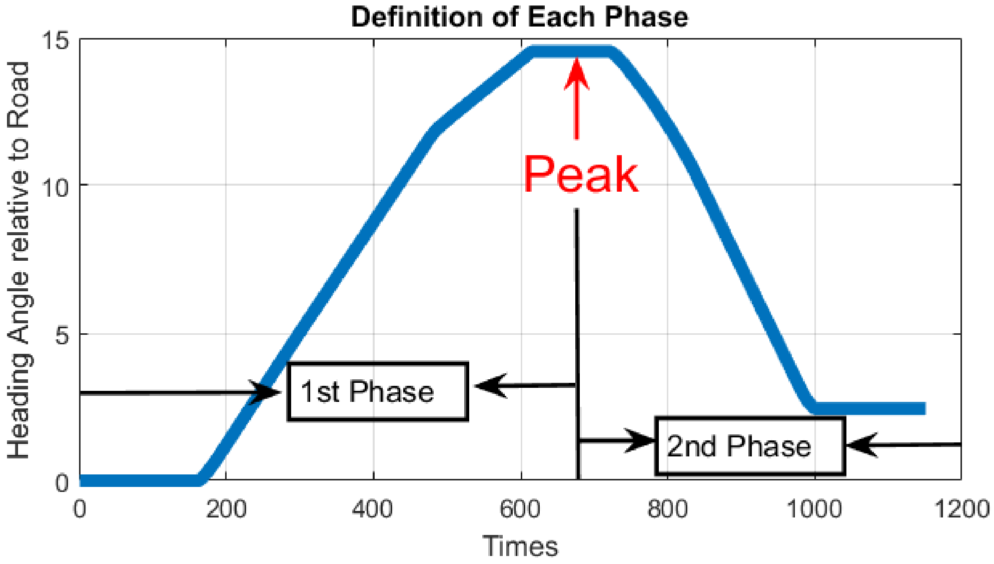

Figure 4 shows the definition of the duration of each phase in a lane-changing (bi-phasic).

Results

We first examined the Return Ratio (RR) for Block 1 with full visual feedback. The prediction is that all participants should demonstrate no problem in lane-changing with full visual feedback. However, the RR over all participants (Block 1, full cue) was only 0.712 (M) ± 0.075 (SE) (see Figure 5). A one-sample t-test was conducted, revealing that this RR was significantly lower than 1.0, t(8) = -3.843, p = 0.005. The results hence surprisingly suggest that participants could not complete a lane-change even when full visual feedback was present. It is very unlikely that participants did not know how to conduct a lane-changing manoeuvre with full visual feedback, hence there remain two possibilities:

1. Some conditions in the experiment are too unusual for typical lane-change.
2. The use of a HMD.

Firstly, we investigated some of the parameters used in this experiment. Since quite a few lane-changing experiments had been carried out in previous studies, we compared the parameters used among these experiments. It turned out that the speed used in this experiment was exceptionally slow, only at 8 km/h. It is quite possible that the low speed prevented participants from conducting lane-change in the given 12 seconds. To validate this assumption, we calculated the duration of first steering phase and second steering phase (see Figure 4) over all participants. Since in this experiment the vehicle's speed was constantly at 8km/h at all times, it is reasonable to expect that participants would spend roughly equal time on each steering phase. However, in Block 1 with full visual feedback, the time spent on the first steering phase over all participants was 9.52s (M) ± 0.51s (SE). In comparison, the remaining 2.48s (M) ± 0.51s (SE), was hence spent on the second steering phase. The results suggest that participants spent 80% (9.5/12) of the duration on the first phase, leaving only 20% (2.5/12) for the second phase. It is very likely that participants were not able to complete the second phase within such a short duration. Secondly, the use of a HMD might be another possibility. Although HMDs provides binocular view, they are usually limited in field of view (e.g. in this thesis we used a projector system comprising a field of view of $160^o \times 45^o$ while this HMD provides $110^o \times 95^o$, despite that this HMD is far closer to the eyes) and they have added mass on head. A number of studies found that the additional mass, moments of inertia, and limited field to view of HMDs are likely to contribute to visual illusion such as underperception of distance (Knapp and Loomis 2004, Willemsen, Colton et al. 2004, Willemsen, Colton et al. 2009). Regardless of the exact root causes, the largely incomplete lane-change in Block 1 with full visual feedback generally makes it impossible to continue analyzing RR for Block 1 with no visual feedback. This is because the incomplete lane-change with full visual feedback had a serious carryover effect on lane-change with no visual feedback. Specifically, the simulated vehicle in all lane-changing blocks was not reset (i.e. making vehicles' heading straight ahead again) after each lane-change manoeuvre, meaning that the initial heading of the vehicle in the second lane change manoeuvre (i.e. lane change with no visual feedback) was simply the heading at which the vehicle aimed at the end of the first lane change manoeuvre (i.e. lane change with full visual feedback). As a consequence, participants might have attempted to finish the incomplete lane change started in the full visual feedback condition. In this case, the participants' lane-changing manoeuvre in the no visual feedback condition included two tasks a). an on-going lane-changing manoeuvre started in the full visual feedback condition; b). a fresh lane-changing manoeuvre in the no visual feedback condition. Unfortunately, there was no appropriate way to distinguish one task from the other. Thus, analysis of the lane-change manoeuvre in Block 1 with no visual feedback will be severely affected by the carryover effect and becomes extremely unreliable.

We then analyzed RRs for all remaining blocks (Block 2, Block 3, Block 4) with full visual feedback only to investigate whether the same issue persisted in other blocks (see Figure 5). RR for reverse lane-changing block was 0.962 (M) ± 0.022 (SE), for parallel-parking block was 0.981 (M) ± 0.029 (SE), and for Block 4 (the block identical to Block 1) was 0.805 (M) ± 0.060 (SE). Interestingly, only in forward lane-changing blocks (Block 1 and Block 4) were participants not able to conduct lane-change within the given 12 seconds, as shown by the low RRs. A repeated Anova conducted on RRs (in full visual feedback conditions only) over all blocks revealed that the effect of blocks was significant, $F(3, 24) = 14.443$, $p < 0.001$. Further pairwise comparisons indicated that RR for Block 1 and RR for Block 4 were both the smallest, $p < 0.05$ (see also Figure 5). Given the results, it would be inappropriate to continue analyzing RR in the no visual feedback condition in Block 4 due to the same carryover effect seen in Block 1. However, it is not problematic to continue analyzing RR for the reverse lane-changing block in no visual feedback condition because participants showed a RR close to 1.0 in the full visual feedback condition in this block. Specifically, a one-sample t-test suggested that the RR in the full visual feedback condition in the reverse lane-changing block was not significantly different from 1.0, $t(8) = -1.719$, $p = 0.124$. This suggests participants performed the reverse lane change with full visual feedback almost perfectly. It also remains feasible to analyze RR in the no visual feedback condition in the parallel-parking block because in this block the vehicle was reset to its original position after each parking manoeuvre. Again, a one-sample t-test showed that RR in the full visual feedback condition in the parallel-parking block was not significantly different from 1.0, $t(8) = -0.667$, $p = 0.524$. The results suggest that participants conducted the paralleling parking manoeuvre reasonably well with full visual feedback.

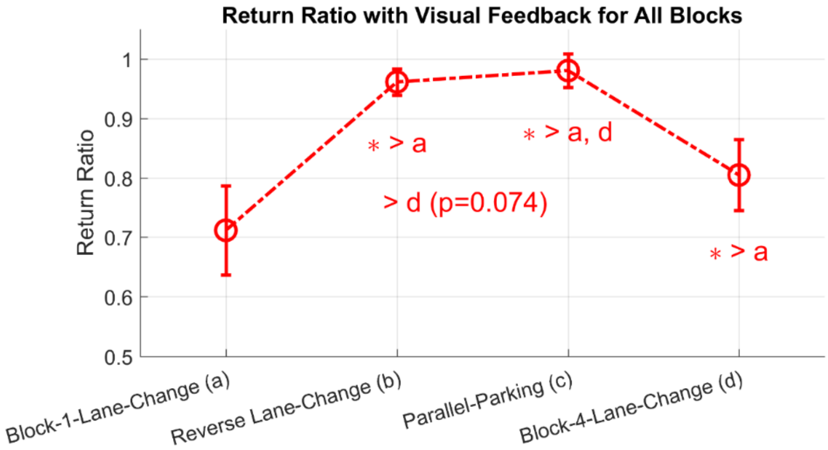

Figure 5 indicates RRs for all blocks (Block 1-4) with visual feedback. Error bars are SE. '' indicates 0.05 level.*

Finally, we turn to analysis for the RR for reverse lane-changing and for parallel-parking with no visual feedback (Figure 6). For the sake of comparison, both no visual feedback conditions (blue line) and full visual feedback conditions (red line) are drawn in Figure 6. RR for reverse lane-changing without visual feedback was 0.746 (M) ± 0.135 (SE), and RR for parallel-parking without visual feedback was 1.205 (M) ± 0.284 (SE). A paired t-test conducted on “RR for full cue” vs. “RR for no cue” (red line vs. blue line) did not find any significant difference between the two: t(8) = 1.676, p = 0.132 for no visual vs. visual in the reserve lane changing block; t(8) = 0.825, p = 0.433 for no visual vs. visual in the parallel parking block. The results generally suggest that, on average, participants performed equally well in the full visual feedback condition and no visual feedback condition in both the reverse lane changing block and the parallel parking block. However, the high SEs for the no visual feedback condition in both blocks suggest that there was a great discrepancy among participants. Indeed, after investigation we found that for the no visual feedback condition in the reverse lane-changing block, participants showed various RRs from as low as 0.17 to as high as 1.43. For the no visual feedback condition in the parallel-parking block, participants showed RRs ranging from 0.16 to 3.06. This indicates that some participants conducted an incomplete bi- phasic manoeuvre (RR < 1) while others conducted an excessive return phase (RR > 1). That said, an excessive return phase does at least suggest that the participant had the intention to conduct a bi-phasic manoeuvre, while an RR considerably lower than 1.0 (such as 0.16) might indicate that the participant was simply carrying out the systematic error shown in Figure 1b. Taken all together, overall participants showed some ability to conduct a return phase during reverse lane-changing and parallel parking with no visual feedback, with relatively few making the classic, systematic error seen during forward lane changing.

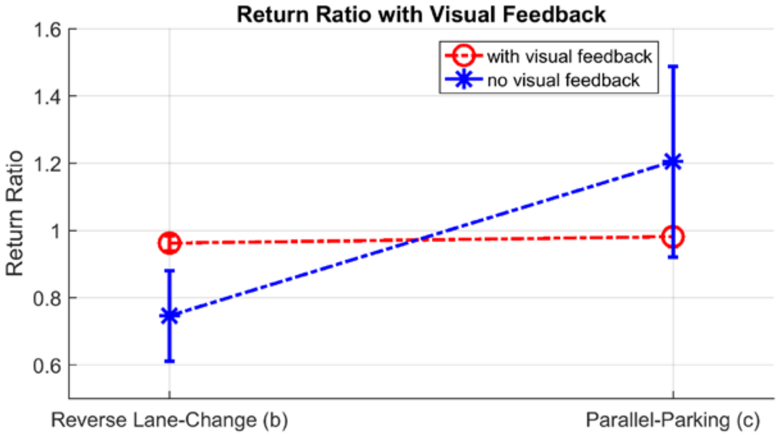

Figure 6 shows RRs for reverse lane-changing block and parallel-parking block. Error bars are SE.

Discussion

Due to the characteristic of this experiment (exceptionally low speed and relatively short duration for the lane changing task), we had serious carryover effects on Block 1 and Block 4. As a result, we cannot analyze participants' behavior in no visual feedback conditions for these two blocks. Consequently, we cannot identify whether participants were naïve or not, i.e. whether they had the intention to conduct a return phase during a lane-change in Block 1 with no visual feedback. We also cannot be sure that the classic error reoccurs at such low forward speeds (8 km/h). These issues represent substantial limitations of the experimental design and should be taken into account in future experiments. That said, this study provides an insight into a daily steering task that, to our best knowledge, has not been systematically examined in previous literatures, probably due to the hardware limitation of traditional monitors. The results, at least, the majority of participants attempted to produce a second, return steering phase when parallel parking in no visual feedback condition. This is interesting because it suggests that the naïve understanding of vehicle control seen in subjects driving forwards and conducting tasks such as lane change and obstacle avoidance, does not replicate to the case of reversing (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009, Xu, Wallis et al. 2014). Future work should aim to fully investigate whether disappearance of this erroneous steering behavior is due to a different internal model being harnessed during reversing. An important starting point would be replication of the classic effect when driving forwards in a HMD at low speeds, to confirm that these two factors are not the underlying cause of the change in outcomes described here.

Chapter Five - Study 4: A Test of Real-World Lane Change

Experiment Lane Change in The Real World

Introduction

One popular attraction at modern theme parks are rides often dubbed “a 4D movie”, in which the additional “Dimension” usually involves physical motion of the viewer. In a typical 4D movie, visitors sit on a motorised platform while watching a movie of a fast-paced journey along a road or flying through space. While the simulated vehicle undergoes intentionally rapid changes in speed and orientation, the visitor is subjected to real movement generated by the seat. The combination of vestibular, somatosensory and visual feedback generally offers an incomparably vivid experience. The effectiveness of this multisensory stimulation points to the fact that self-motion perception incorporates an array of non-visual cues. Indeed, since the human vestibular system, for example, is very sensitive to both linear acceleration and rotations (for a comprehensive review on vestibular systems see (Angelaki and Cullen 2008)), it seems likely that at least some non-visual cues play a role in human navigation. Indeed, Telford, Ohmi, et al. found that vestibular cues contribute to self-locomotion during walking and passive motion, especially when visual feedback is unreliable (Telford, Howard et al. 1995, Ohmi 1996); and Harris, Bertin, et al. report that vestibular systems are associated with perception of the distance and directions travelled (Harris, Jenkin et al. 2000, Bertin and Berthoz 2004).

Although the role of non-visual cues has been acknowledged in the past it is only recently that we have come to appreciate how significant their role may be. Carefully controlled studies conducted in monkeys suggest that vestibular information supports a level of heading perception comparable in accuracy to that achieved using visual cues (Gu, DeAngelis et al. 2007, Gu, Angelaki et al. 2008). Follow-up studies have likewise confirmed this, describing how the brain integrates vestibular cues and visual feedback in an approximately statistically optimal fashion (Fetsch, Turner et al. 2009, Butler, Smith et al. 2010, Campos, Byrne et al. 2010, Fetsch, Pouget et al. 2012, Saunders 2014, Butler, Campos et al. 2015). Interestingly, these studies often suggest that vestibular cues are actually weighted slightly more than they should be, given their accuracy, resulting in a modest deviation from an ideal observer model (Fetsch, Turner et al. 2009, Butler, Smith et al. 2010, Campos, Byrne et al. 2010, de Winkel, Weesie et al. 2010, Fetsch, Pouget et al.

2012). Hence it is now widely believed that vestibular cues play a significant role in the control of self-locomotion.

But what about driving? Among our various everyday modes of locomotion driving certainly provides plenty of situations in which vestibular stimulation is strong (e.g. during speed regulation) and heading changes (i.e. cornering, lane changing, etc.). Compared to walking, vestibular cues received steering are likely to exceed the perception threshold more often due to vehicle dynamics (e.g. the ability to accelerate the vehicle). If vestibular cues are found useful during walking, it is likely that such cues would even participate more in the control of steering. Nonetheless, relatively little is known about the role of vestibular (or other non-visual) cues in driving and that is the focus of this paper. To tackle this question, we have chosen to focus on the task of lane changing, the reasons for which will hopefully become apparent after a short review of what we know about lane changing behaviour.

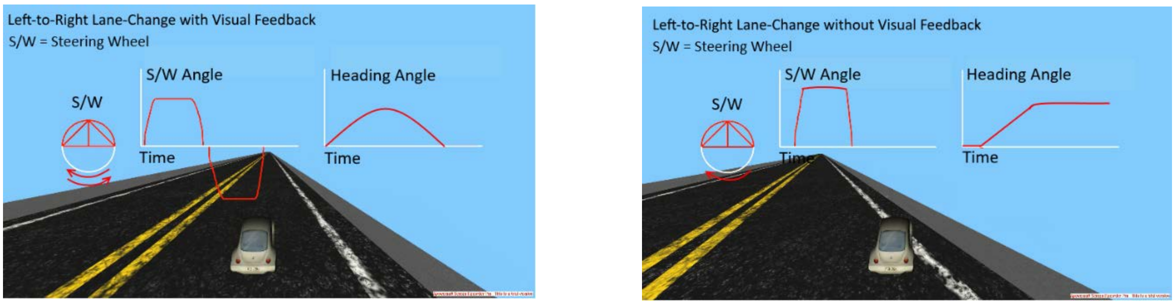

Figure 1 illustrates the pattern of changes of steering wheel angle and heading angle during a typical lane change (change from left lane to right lane) with and without visual feedback. Note that the steering wheel angle against time illustrates two symmetrical steering phases for a typical correct lane change in the visual feedback condition (Left). In the no visual feedback condition, however, drivers only complete the first steering phase and omit the second one (Right).

Lane changing consists of a bi-phasic manoeuvre (Figure 1, Left) which can be characterized as two steering phases (an outward steering phase required to cross into the adjoining lane, followed by a return steering phase required to straighten the vehicle). Our lab has been studying lane changing behaviour for some years, motivated by our original discovery that in a fixed-base simulator, in which sensory cues such as proprioception of inertia, body tilt, etc. were conspicuously lacking, drivers make a consistent, repeated steering error (Wallis, Chatziastros et al. 2002, Xu, Wallis et al. 2014) (see also Figure 1, Right). In a later study, we replicated the lane change results using a driving simulator mounted on a motion platform which was capable of providing motion about the three primary axes of rotation. The fact that drivers continued to make the same mistakes in the motion-based simulator, appears to suggest that vestibular cues play little or no role in controlling a lane change manoeuvre (Wallis, Chatziastros et al. 2007). The results were in general accord with those of Wilkie and Wann (2005), who asked participants to steer a vehicle towards a fixated target while manipulating retinal flow, gaze angle, and vestibular information. The vestibular information was provided by rotating a motorized chair in accordance with the participant's steering movements. The authors reported that veridical vestibular stimulation did not enhance performance. They also found that incorrect feedback did not reduce performance, again suggesting that vestibular input was not incorporated in steering control at all.

Hence it appears that vestibular cues are of little consequence in steering tasks such lane change, but this seems to be at odds with the work on self-locomotion described above. One obvious limitation of the driving studies is that the motion platforms could not generate translational movement, only rotations. Due to the characteristics of modern vehicles, a car cannot be turned while it is not moving, whereas a motion platform can do a pivot turn / tilt without moving forward. Even 6dof motion platforms can only offer limited lateral acceleration preventing drivers in simulators from experiencing the full, natural inertial feedback experienced during steering, leading to what is, in effect, a cue-conflict situation in which the pivot rotation combined with the zero-linear speed does not match real vehicle dynamics. Given that vestibular cues have been implicated in the control of self-locomotion, we believe it is of an interest to examine whether the addition of full, natural inertial feedback provided by a real vehicle might trigger more natural steering responses. In particular, we thought it informative to test the aforementioned lane change tasks to see if appropriate vestibular and proprioceptive stimulation might suffice to produce correct lane change behaviour even in the absence of visual feedback. Although experiments of this kind have been attempted before, the most relevant study, conducted by (Godthelp 1985)using a real car, provided subjects with knowledge of results, making it hard to interpret (Wallis, Chatziastros et al. 2002). A second study, based on data from a mobility cart, concluded that non-visual cues play a role in lane changing (Macuga, Beall et al. 2007). Unfortunately, the cart travelled at extremely low speeds (6km/h), and the protocols employed suggest that half of the participants may not have qualified as truly naïve as they had been exposed to a related path-following task before testing. This paper describes an experiment in which we run truly naïve participants in a fully instrumented family saloon at realistic diving speeds under periods of visual occlusion, and then go on to verify that they remain naïve after this real-world testing.

Method

In order to fully investigate the difference in lane change performance between a fixed-base simluator (vestibular and somatosensory information is missing) and real vehicle (all non-visual information is present), this experiment involved three parts: 1). A test using a fixed-base driving simulator that acts as a baseline test; 2). A test using a real car in the real world. 3). A follow-up test indentical to Part 1 acting as a post test. Part 1 served as a baseline test but also as a screening test process prior to the real world test. We only recruited participants who showed systematic errors in the no visual feedback condition in Part 1. This is because if participants can already produce a return phase on a fixed-base simulator with no visual feedback, it is unnecessary to test them again with a real car. Part 3 severed as a post-test to see if participants learned anything in Part 2.

Procedure

For both Part 1 and Part 3, participants were required to conduct a lane change in two conditions in a fixed-base driving simulator --- with and without visual feedback. In each condition, participants were asked to conduct five left and five right lane changes in a random order, resulting in a 2(feedback/no feedback) × 2 (lane-change directions) design. Each lane change was repeated five time resulting in a total of 20 lane changes (Table 1). At the beginning of each trial, the vehicle was placed in either the left lane or the right lane (randomly chosen). The vehicle then remained still untill the participant pressed a button embedded on the steering wheel. Once pressed, the vehicle moved forwards at a constant speed of 45 km/h, matching the speed in the real world test. Four seconds after pressing the button, a message was displayed on the screen to remind participants to conduct a lane change to the opposite lane. 12 seconds were given to complete the lane change, after which the visual feedback was removed. 2 seconds after the removing feedback, participants were instructed to conduct a lane change in the direction opposite to the first lane change. 12 seconds were again given to complete that manoeuvre, after which the trial terminated and a new trial began.

Table 1 *indicates the procedure of each trial in Part 1 and Part 3.*

Contents of Each Trial (numbers = duration in seconds)		Repetition
First lane change with full visual feedback (12s)	Second lane change with no visual feedback (12s)	10
Procedure of each trial: 4s (get-ready time) + 12s (lane change with visual feedback) + 2s (get-ready time) + 12’ (lane change with no visual feedback)		

For Part 2, eligibile participants chosen from Part 1 were invited to participate. In the real car participants followed a similar procedure with Part 1 but this time they drove an instrumented vehicle in the real world (Figure 2b and Figure 2c). To control varables involved in Part 2, participants were asked not to touch the brake or the accelerator at all. An experienced driver sat in the passenger seat, controlling the brake and the accelerator via a dual control system. In this way we were able to maintain the speed at a desired level (in this case around 45km/h) and ensure every participant moved at approximately the same speed during the entire experiment. The detailed procedure of each no feedback trial in Part 2 can be described in 6 steps:

1. The direction of required lane change and test condition is communicated verbally to the subject (e.g. plese conduct a left lane change with visual feedback).
2. The experimenter pressed the accelerator and sped up to the desired speed (i.e. around 45km/h) in approximately 4s.
3. Two seconds after Step 1, participants heard a ‘Da’ sound which acted as a warning signal reminding them to get ready for the upcoming task. Three seconds after Step 1, the shutter glasses were closed. Four secs after Step 1, participants would hear a ‘Ding’ sound which acted as a signal to prompt them to carry out the manouvre.
4. Participants executed a lane change.
5. Participants then verbally reported “OK” once they believed they had completed the manouvre.
6. The experimenter steered the car back to the starting point (with the shutter glasses remaining closed). The shutter glasses then opened and the next trial began (repeating 20 times: 10 trials with visual feedback and 10 without).

In the case of a visual feedback trial the procedures were the same as described above except the shutter glasses were not activated at any point during the trial. The commands (i.e. left/right lane changes) issued by the author were pre-generated in a random order. Participants had no prior knowledge about the order of left/right lane changes. Nonetheless, to mimic the experiment of Part 1 and Wallis and colleagues’ previous experiments (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Xu, Wallis et al. 2014), lane changes with visual feedback and lane changes with no visual feedback always appeared in pairs. That is, a lane change with visual feedback was always followed by a lane change without visual feedback (in opposite directions). Participants had no feedback about their lane change performance in the no visual feedback condition.

Apparatus

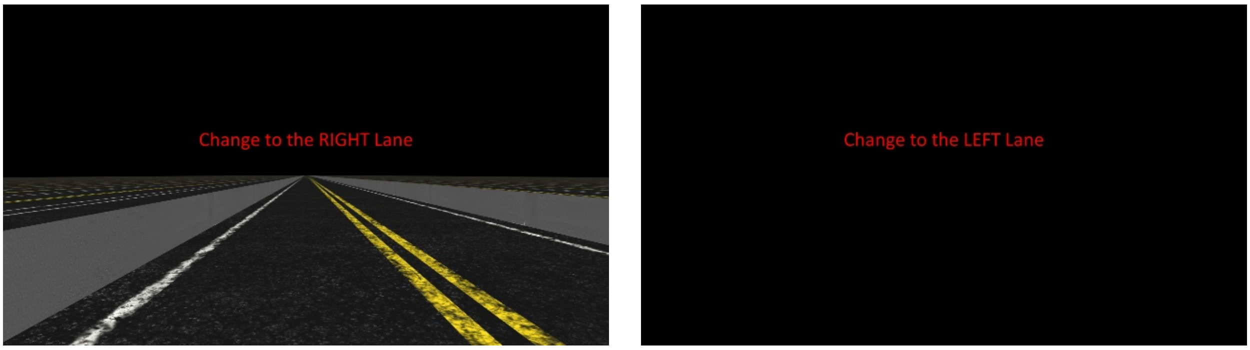

Figure 2a illusrates the virtual environment of Part 1 and Part 3. Left: full visual feedback condtion. Right: no visual feedback condition.

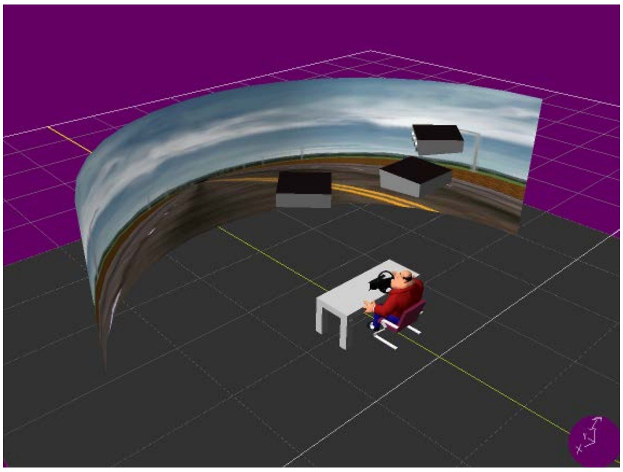

Figure 2b illusrates the apparatus used in Part 1 and Part 3. The apparatus consisted of three projectors, a curved screen, and a steering wheel.

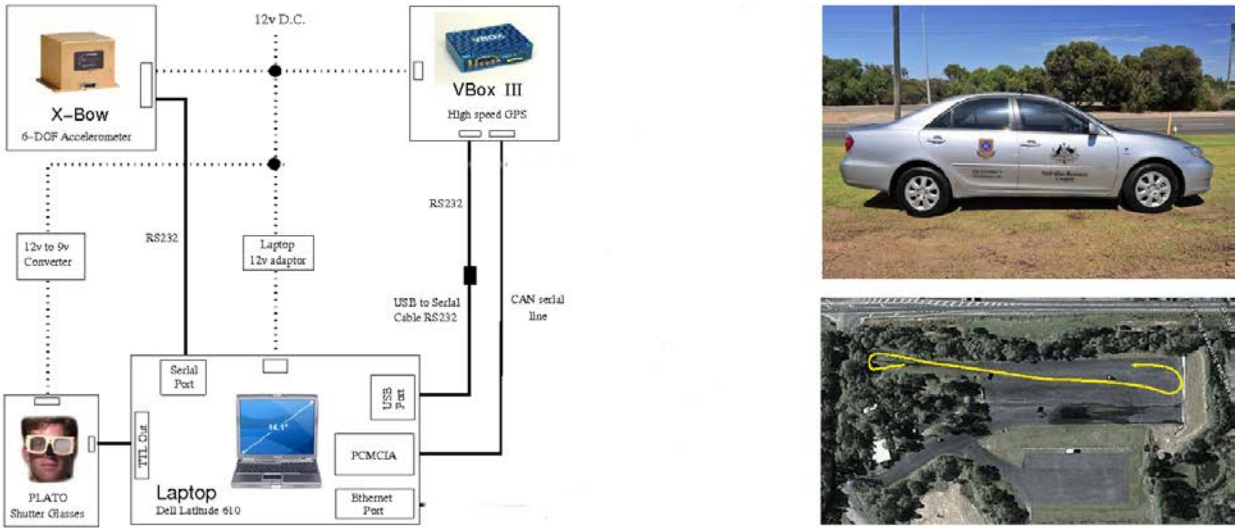

Figure 2c illustrates the devices employed as well as the instrumented car, and an aerial shot of the test site (yellow line show a typical trajectory driven by the experimenter. The devices included a six DOF accelerometer, high-precision differential GPS, a pair of shutter glasses, and a laptop running control and data acquisition software written by the lead Author in C++).

Figure 2d illustrates a typical view of the test site. Four lines were drawn to indicate three lanes. Participants drove in the central lane at the beginning of each trial and then changed to left or right lane. The lane marks appear a little faint in the photograph but were drawn with brightly coloured chalk and so were very easy to see at the test site.

The visual environment for both Part 1 and Part 3 is shown in Figure 2a and Figure 2b. A large projection system consisting of three Panasonic RZ-470 projectors was used, providing a large field of view ($160^o \times 45.5^o$). The resolution of the projection system was 5760 × 1080. Participants were seated about 2.7 meters aways from the surface of the screen approximately at the screen's centre of curvture and used a Logitech MOMO force-field steering wheel to control the vehicle. For Part 2, an instrumented car (Toyota Camry), a high-precision differential GPS, a 6 degree-of-freedom accelerometer, a pair of shutter glasses, a laptop, and control software were used to do the experiment (Figure 2c). The car was a dual control vehicle with two sets of brake and accelerator, but note that there was only one steering wheel located at the driver seat. A driver training centre located in Mt. Cotton, Brisbane, Australia was hired to run the experiment (Figure 2d). Three lanes were provided at the test site, each of which was about 100 meters long and 3.5 meters wide. Note that in each trial the vehicle started about 25 meters away from the entrance of the middle lane, allowing the experimenter to speed up the vehicle to the desired speed level before going into the middle lane. During the experiment, the GPS was running at 100Hz while the accelerometer was running at 160Hz. In the control software, CPU time (unit was milliseconds, using BOOST library to maintain best accuracy and precision under windows system) was used as a reference time to sync the GPS data and accelerometer data for subsequent data analysis. The control software collected all the data as well as issued commands to the shutter glass (i.e. open/close the shutter to give visual/no visual feedback).

Analysis

The Return Ratio (RR for short, see Figure 3 for definition, see also (Macuga, Beall et al. 2007, Wallis, Chatziastros et al. 2007)) was used to measure whether a participant conducted a lane change successfully. RR is a convenient metric for quantifying the return phase of a lane-change manoeuvre. RR is defined as the ratio of the heading change seen during the return (second) steering movement, divided by the heading change seen during the outward (first) steering movement. If H_{peak} denotes the peak value of heading, and H_{final} the final value of heading, we have

$$\mathrm{RR} = \frac{H_{peak} - H_{final}}{H_{peak}}$$

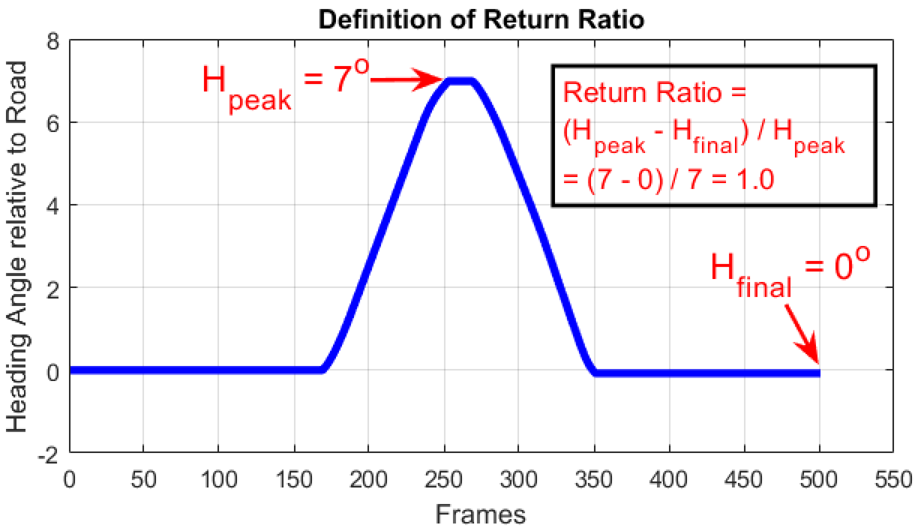

Figure 3 Heading changes for one subject during a lane-change with full visual feedback. The Return Ratio (RR for short), is defined as (H_{Peak} – H_{Final}) / H_{Peak}.

Obviously, a RR close to 1 indicates an almost perfect lane change (as is Figure 3), while RR close to 0 indicates a lane change with little or no return phase (as is Figure 1, Right). It is important to notice that RR only measures whether a bi-phasic manoeuvre is conducted, in other words, to what extent the vehicle’s heading returns to where it started before the lane change began. RR does not tell us anything about the vehicle’s lateral position, i.e. RR does not tell us whether the vehicle is moved precisely to the adjacent lane after a lane change. We used RR only for measuring whether a manoeuvre is bi-phasic or not. As a consequence, “perfect lane change” in this paper does not refer to precise control of the vehicle's lateral position but to the shape of the heading profile (see Figure 3). The reason we used RR instead of measurement of lateral position is that it may be difficult to move the vehicle precisely to the adjacent lane in the no visual feedback condition (which may involve spatial memory), but it is feasible to conduct a bi-phasic manoeuvre even without visual feedback (which only requires an intention of the second, return phase). In this study, we were more interested in whether the full, natural inertial experience could trigger a return steering phase during lane changing, rather than testing our participants' ability to laterally displace the vehicle by the correct amount.

In both Part 1 and Part 3, the analysis of Return Ratio used heading profiles recorded by the driving simulator. In Part 2, the data used to analyze RR were heading profiles recorded by the GPS system. In Part 2, yaw rate, roll acceleration, and speed were also provided as complement to RR (see Appendix). For all three parts, the left / right lane changes were collapsed for analysis.

Due to the nature of the real-world experiment, a certain amount of noise is expected in the data. To minimize the influence of noise, a spline function provided by MATLAB R2016b was used to fit the real heading data recorded by GPS. Supplementary data such as yaw rate, roll acceleration, and speed were not fitted because they were not used in any mathematic analysis. For the fitted heading data, the goodness-of-fit was calculated through both R-square and RMSE. The mean R-square was 0.9740 ± 0.0164 (M ± SD), and the mean RMSE was 0.0490 ± 0.0138 (M ± SD). Note that the mean RMSE was very small compared to the theoretical largest mean RMSE value “2”. Thus, both the R-square and RMSE suggest a reasonably good fit. Finally, heading angle was normalized to be within [-1, 1] prior to analysis to avoid the influence brought by different steering amplitudes due to individual driver differences. This explains why the theoretical largest mean RMSE was 2 --- assuming that the actual heading data was a horizontal line at heading angle = 1, whereas the fitted one was a horizontal line at heading angle = -1.

In Part 1 and 3 a small number of trials were excluded due to participants not obeying instructions (i.e. they did not touch the steering wheel or they held it at a particular angle without releasing during the entire trial, etc.) about 3% trials were excluded on this basis. Due to hardware problems, a total of 8 trials' data excluded in real-car experiment (Part 2), representing about 2% of trials.

Participants

Participants were recruited from three universities in Brisbane, Australia. 41 participants consisting of 22 males and 19 females, aging from 20 ~ 30, were involved in the fixed-base simulator experiment (Part 1) for the initial screening process. All participants had normal or corrected-to-normal vision and had at least 2 years' driving experience. 10 participants showed a reasonably good ability to produce a return phase in the simulator and so were subsequently excluded from further test. The remaining 32 subjects showed little or no return phase (for quantitative analysis see Results Section) and were invited to do the real car experiment. Finally, 17 out of those 32 subjects arranged time to do the real car experiment. The real car experiment required an entire afternoon, with approximately four hours on the test site and 1.5 hours travelling between the site and the University. At the test site, every participant spent about 1 hour doing twenty trials (10 with visual feedback and 10 without). An extra 10-15 minutes were given to every participant to familiarize themselves with the car and the site before the experiment. More practice time was also available if participants felt they needed more time. All participants had at least 2 years driving experience. All participants had no problem in driving the real vehicle during the entire experiment. Those 17 participants who did the real car experiment were also involved in Part 3 to re-examine their abilities to change lanes in the fixed-base simulator after being exposed to the real car tests. This study was approved by the ethical committee of University of Queensland, Australia.

One concern might be that we excluded 25% (10 out of 41) participants in this experiment. We should mention that as time went on we found an increasing number of participants that were "non-naïve". This was presumably due to that we had tested more than 100 participants prior to this experiment, not to mention similar experiments were conducted in this lab long before the author's PhD commencement. It is likely that the experimental hypothesis was known by a large number of people in this university. This is also reflected by the fact that we did not have a "screening process" for the very first experiment (Study 1, Expt. 1) but we introduced that process for later experiments as more and more participants were involved.

The approach we used to exclude "non-naïve" participants was based on the measurement of Return Ratio. We excluded participants who achieved a Return Ratio >= 0.5 in lane change without visual feedback in Part 1. This came with two reasons: i). If someone's RR was already > 0.5 (for example, 0.7) in no visual feedback condition and achieved RR = 0.9 in real-world test, it would be less convincing compared to that RR increased from 0.2 in no visual feedback condition to 0.9 in real-world test; ii). those who achieved RR > 0.5 likely had above-average knowledge about lane change.

Results

Part 1

For simplicity, analysis for all 41 participants was labelled “All”, analysis for those 10 excluded participants was labelled “NON-NAIVE” to emphasize their ability to change lane with no visual feedback, and analysis for those 17 participants who went on to participate in Part 2 and Part 3 was labelled “Real-Car” to clearly indicate their participation in Part 2 and Part 3. RR for the three groups of participants are shown in Figure 4. Specifically, the average RR for all participants was 0.302(M) ± 0.043(SE), for “non-naive” participants was 0.711(M) ± 0.058(SE), and for “real-car” participants was 0.157(SE) ± 0.027(SE). A one-way ANOVE shows the effect of groups is significant, F(2, 67) = 18.275, $p < 0.001$. Further pairwise comparisons indicate that only the RR for “non-naïve” participants is significantly larger than the rest two, $p < 0.001$. The results generally suggest that for the majority of participants, a classic lane-changing error was observed. In contrast, the group of “non-naïve” participants displayed above-average abilities to conduct lane change without visual feedback, and as a result they were excluded for further tests. We also calculated the within-subject standard deviation (SD) for the group of “Real-Car” participants. The calculation of SD was based on all trails participants conducted in each condition (i.e. with and without visual feedback). A small SD should reflect consistent steering behaviour across all trials in any given condition. The within-subject SD for “Real Car” participants with visual feedback was 0.155(M) ± 0.015(SE), whereas that without visual feedback was 0.192(M) ± 0.032(SE). A paired t-test shows they are not significantly different, t(16) = 1.301, $p = 0.318$. This suggests that participants performed equally consistently across visual/no visual feedback condition. The within-subject SD in Part 1 can be used as a reference in interpreting later results.

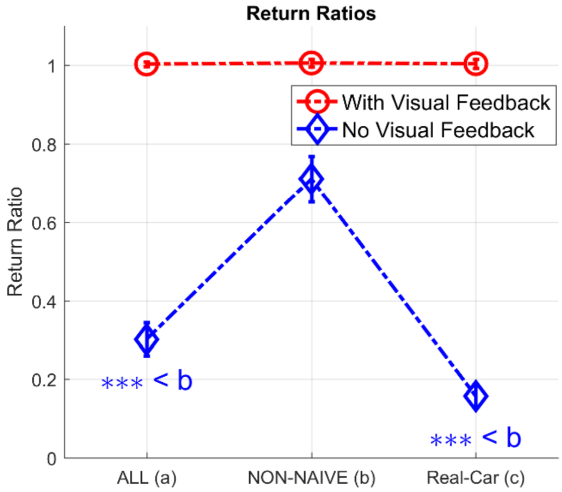

*Figure 4 demonstrates RR for all three groups of participants in two visual feedback conditions. Paired t-tests reveal that all three groups showed significantly lower RR in no visual feedback condition, p < 0.001, see red line vs. blue line. t-tests also show that "Real-Car (c)" participants demonstrated the smallest RR among all three groups in no visual feedback condition, p < 0.001, see blue line. '***' indicates 0.001 level.*

Part 2

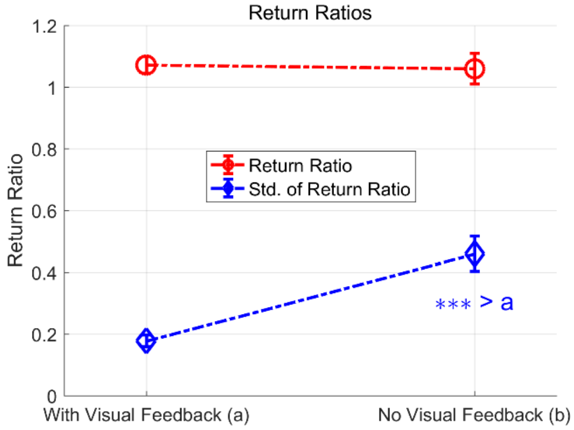

*Figure 5 indicates RR over all participants (the 17 participants that participated in Part 2) in two visual feedback conditions (red line). Figure 5 also shows within-subject standard deviation on RR over all participants in two visual feedback conditions (blue line). '***' indicates 0.001 level.*

Heading data were first fitted with splines as described in the Analysis section. Figure 6a and Figure 6b show the fitted data (red line) and raw data (blue dots). RR was then calculated based on fitted splines. Figure 5 shows RR (red line) for lane change with and without visual feedback. First, RR over all 17 participants with visual feedback was very close to 1 (1.07 (M) ± 0.027 (SE)), as expected. The results suggest that: i) participants conducted lane changes perfectly with a real car with visual feedback, as one would expect; ii) the devices and control software were in good working condition during data collection;

iii) the fitted splines matched the raw data reasonably well. Second, RR in the no visual feedback condition was also around 1 (1.06 (M) ± 0.05 (SE)). A paired t-test was performed on both RRs (with and without visual feedback), revealing that they were not significantly different: t(16) = 0.240, p = 0.814. This suggests that, on average, participants did produce a complete return steering phase during lane change in the real world with no visual feedback. Another surprising fact is that the small SE seen among participants in the no visual feedback condition (i.e. SE = 0.05) suggests that every participant, on average, conducted a lane change almost perfectly without visual feedback. Indeed, after investigation we found that in the no visual feedback condition participants showed RRs from 0.76 to 1.39, implying the effect was consistent for every participant.

We next analysed the within-subject SD on RR with and without visual feedback. As shown in Figure 5 (blue line), the within-subject SD for lane change in the no visual feedback condition was large: 0.46(M) ± 0.058 (SE). In comparison, the within-subject SD for lane change with visual feedback was much smaller: 0.18(M) ± 0.019 (SE), t(16) = 4.744, p <= 0.001, effect size d = 1.522.

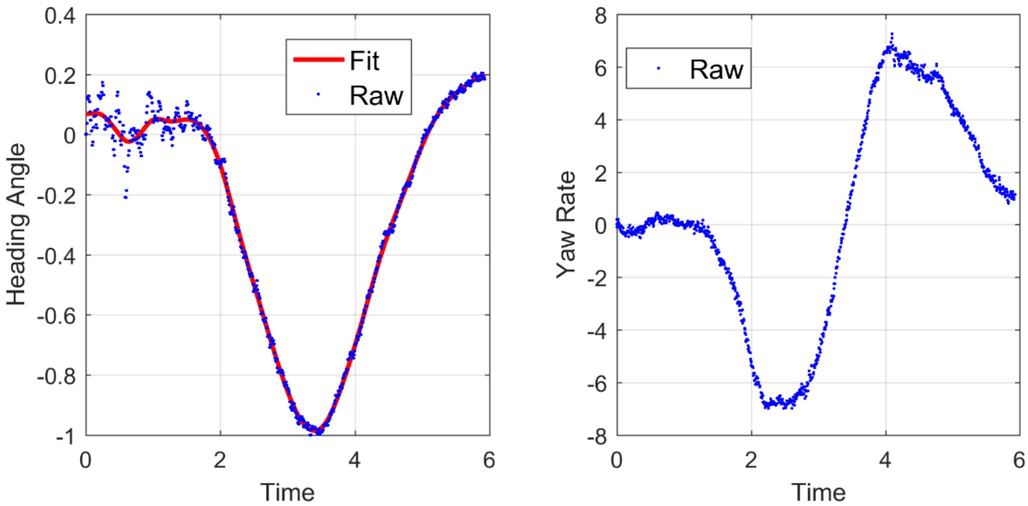

Figure 6a illustrates the heading profiles (Left) and yaw rate (Right) in one trial with visual feedback.

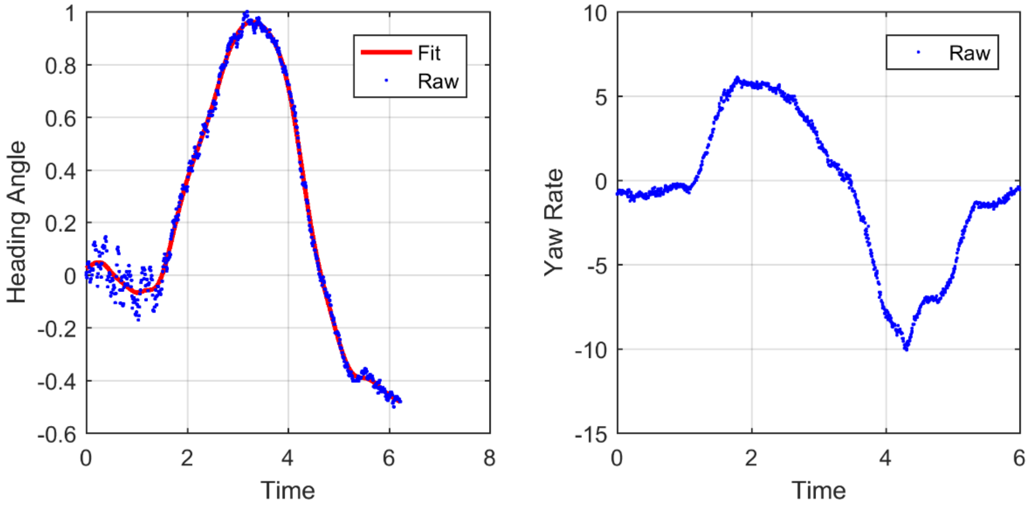

Figure 6b illustrates the heading profiles (Left) and yaw rate (Right) in one trial without visual feedback.

Generally, the results show that even without visual feedback every participant still performed an on average correct lane change manoeuvre in a real vehicle. As described in the Analysis section, "correct lane change" without visual feedback in this paper refers to a bi-phasic manoeuvre, rather than a precise change of vehicle's lateral position (i.e. from current lane to adjacent lane). On the other hand, the large SD in the no visual feedback condition suggests that participants could not produce a reliable/consistent response in the absence of visual feedback. In fact, without visual feedback participants often either oversteered (RR > 1) or understeered (RR < 1). Figure 7 shows RR per trial for three typical participants in the no visual feedback condition. The considerable fluctuations of RR suggest that without visual feedback participants could not properly estimate the size of a return phase. That said, there was no evidence that the response was biased in any way, that is, on average the RR was very close to 1. By contrast, in Part 1 their RRs in darkness were all significantly smaller than 1.0 (Figure 4), not to mention the comparable SD across visual/no visual conditions, indicating a systematic, consistent steering error across trials. This discrepancy reveals fundamentally different steering behaviours between the fixed-base simulator and the real vehicle. In the former the steering error is by no means random, whereas in the latter the steering error is likely due to a range of random factors (i.e. participants could not estimate the size of each steering phase due to absence of visual feedback, participants could not recall the road width and an appropriate steering phase corresponding to that road width, etc.). Supplementary data such as the average speed, roll acceleration, and yaw rate can be found in the Appendix.

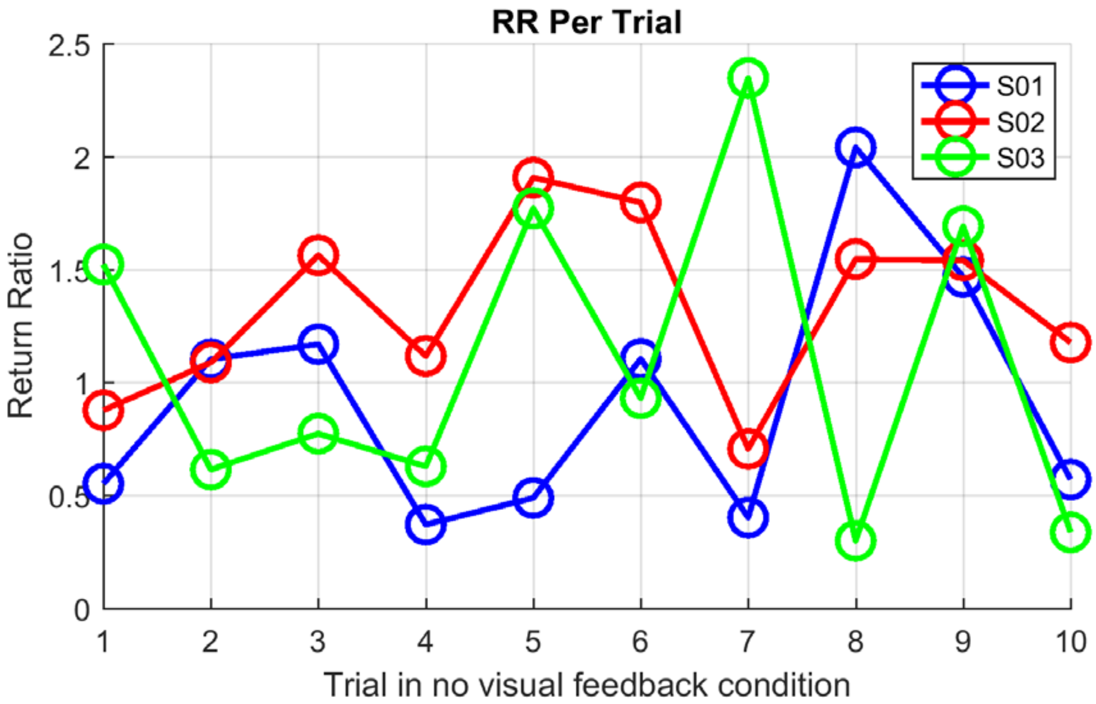

Figure 7 shows three typical participants' RR per trial in no visual feedback condition. RR fluctuated frequently across all 10 trials in no visual feedback condition, indicating that participants could not generate a proper, complete return phase steadily.

Part 3

Part 3 was a post-test that aimed to examine whether participants' behaviour was changed after being exposed to the real-car experiment. 17 participants who were tested on the real vehicle were again tested in Part 3 on a fixed-base simulator. In Part 3, RR over all 17 participants with visual feedback was 0.99 (M) ± 0.01 (SE), whereas RR in the no visual feedback condition was 0.31 (M) ± 0.04 (SE). The latter was significantly smaller than the former, $t(16) = 16.078$, $p < 0.001$, effect size $d = 4.741$. As can be seen, in Part 3 RR in the no visual feedback condition decreased dramatically compared to that in Part 2, suggesting that participants omitted a return phase by a large margin in the fixed-base simulator. Again, the within-subject SD was calculated. The within-subject SD with visual feedback was 0.130(M) ± 0.016(SE), whereas that without visual feedback was 0.206(M) ± 0.027(SE). A paired t-test revealed that the latter is significantly larger than the former, $t(16) = 2.271$, $p = 0.037$, effect size $d = 0.727$. In contrast to Part 2, the RR drastically decreased in the no visual feedback condition. The small difference on SD across visual/no visual condition demonstrates a great change on steering behaviour compared to Part 2 --- that participants showed generally comparable consistency on steering movements in two conditions. Note that the SD in no visual feedback condition in Part 3 (0.206(M) ± 0.027(SE)) was not significantly different from that in Part 1 (0.192(M) ± 0.032(SE)), $t(16) = 0.426$, $p = 0.676$.

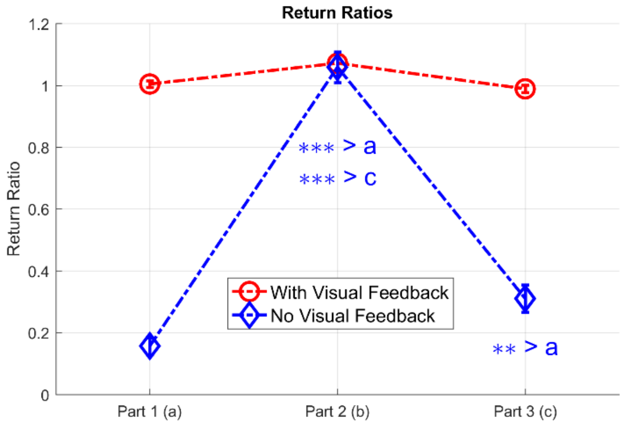

*Figure 8 indicates RRs for those 17 participants across all three experimental parts with and without visual feedback. '**' indicates 0.01 level and '***' indicates 0.001 level.*

Figure 8 presents all RRs with and without visual feedback for Part 1, Part 2, and Part 3. A repeated ANOVA was performed on "RR with No Visual Feedback" over Part 1, Part 2, and Part 3. The ANOVA results show that the effect of session (Part 1/2/3) was significant, $F(2, 32) = 167.292$, $p < 0.001$, $\eta^2 = 0.913$. Further comparisons revealed that: i) RR with no visual feedback in Part 2 (real-car experiment) was the greatest, $p < 0.001$; ii) RR with no visual feedback in Part 3 (post-car experiment) was larger than that in Part 1, $p = 0.007$, suggesting a small carryover effect from Part 2, although this was too minor to prevent systematic errors reoccurring. Only in Part 2 did the participants perform an on average correct lane change manoeuvre (RR ≈ 1). Overall, the results strongly suggest that full, natural inertial cues provided with by a real vehicle significantly improved drivers' lane change performance in the no visual feedback condition.

Discussion

The results of the three phases of the experiment point to the fact that participants perform a lane-changing task very differently when tested in a fixed-based simulator as compared with a real vehicle. Participants were able to conduct a return phase with a real vehicle without visual feedback but repeatedly failed to do so in a fixed-base simulator. Such differences persisted even after being exposed to the task in the real vehicle. The results thus strongly suggest that vestibular (and other non-visual) feedback provided by the real vehicle is sufficient to trigger the second, return phase in a lane change manoeuvre.

This study shows that vestibular cues contribute to everyday steering tasks such as those typified by a lane change. The results are generally consistent with previous studies suggesting that vestibular information is central to self-locomotion (Telford, Howard et al.

1995, Ohmi 1996, Gu, DeAngelis et al. 2007, Gu, Angelaki et al. 2008, Fetsch, Turner et al. 2009, Butler, Smith et al. 2010, Campos, Byrne et al. 2010, de Winkel, Weesie et al. 2010, Fetsch, Pouget et al. 2012, Saunders 2014, Butler, Campos et al. 2015). Nonetheless, our study is different from others in two major aspects. First, we used a real vehicle offering full, natural inertial feedback at an everyday driving speed at 45 km /h, rather than a motion platform providing limited vestibular experience. Second, we used an active steering task rather than heading perception task during passive motion. Consequently, this study significantly generalizes current discoveries on vestibular (and other non-visual) cues.

An interesting question emerging from our study is whether the dramatic difference in steering behavior in the simulator versus real-world, suggests that drivers have conflicting knowledge of how to conduct a lane change. Based on simulator studies, it has been proposed that drivers have a misunderstanding of vehicle dynamics --- they mistakenly believe they can change the vehicle's lateral position without altering their heading, but in fact rotation of a steering wheel changes the vehicle's heading over time and this then leads to incremental changes in lateral position (making it a 2nd order control device for lateral position) (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009, Xu, Wallis et al. 2014). Conversely, the real vehicle test suggests that drivers are, on some level, sensitive to a vehicle's true dynamics, leading them to produce an appropriate bi-phasic manoeuvre. This discrepancy implies that drivers may possess an internal model (or a simple heuristic) driven by non-visual cues. One possibility is that drivers expect two, opposite centripetal forces to act on them over the course of a lane change. As can be seen in Figure 3 of the Appendix, the average peak roll acceleration during a lane change was in the order of 0.2g in this study, well above the perception threshold reported in previous studies (e.g. (Gu, DeAngelis et al. 2007)). Each peak may correspond to the feeling of being "pushed" sideways by the car. In contrast, when both visual feedback and vestibular information are lacking, drivers have to rely on their incorrect internal representation of vehicle dynamics to conduct a lane change, one might even speculate that the absence of the first centripetal shove contributes to suppression of the second steering movement. This hypothesis emphasizes the role of online, non-visual information during steering. The idea is not without precedent, especially in the processing of second order relations. Zago et al. have proposed that vestibular systems are of crucial importance in estimating the time-to-contact of free falling objects (Zago and Lacquaniti 2005, Zago, McIntyre et al. 2008).

This study also lends further support to the proposal that steering errors reported for lane changing in a fixed-base simulator are indeed due to a fundamental misunderstanding of vehicle dynamics. An alternative suggestion might be that drivers require a target to steer towards or may produce a weakened response which decays over time, leading to RR values below 1. However, the real vehicle test clearly shows that in the case that drivers are able to conduct a lane change without visual feedback, they produce an RR that, on average, does not differ significantly from 1. Although subjects may show variability in steering movements trial by trial, no overall bias should be expected. This is further corroborated by the fact that the amplitude and duration of the first phase produced in a simulator does not differ whether visual feedback is available or not (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007).

It is important to mention that a limitation of this study, is that the lane length (100 meters) in the test site might be relatively short compared to a typical lane on a standard road. We observed that in order to fit a lane change within the provided lane on the test site, a few participants preferred to conduct large steering movements during lane change manoeuvre, resulting in large roll acceleration (on average 0.2g, see Appendix). Since drivers are likely to conduct lane change more gently on a standard road, this limitation might make the results less ecologically valid. One approach might be to reduce the speed, e.g. from 45km/h to 30km/h or less. Nonetheless, a severe decrease of speed may also violate ecological validity. During our pilot study, in which a slow speed, 20km/h, was used, we observed that the long task duration and the undemanding situation created by the unusual low speed encouraged participants to pay attention to their steering movements during manoeuvres, e.g. participants did not have to monitor the road frequently so they observed their steering movements instead. As a result, a carryover effect caused by observation and self-learning may pollute the results. An ideal solution, therefore, would be to create a long lane (e.g. 150~200 meters long), allowing a gentle lane change manoeuvre being conducted at an everyday driving speed.

Another concern might be that in the road test not only vestibular cues were involved, but also cues such as engine sound, force-feedback from steering wheel, body variations caused by car movements, proprioception, etc. It is possible that those cues also play a part in the road test. That said, we believe that vestibular signals are the most likely source of useful information for a variety of reasons. First, the engine sound was only noticeable during acceleration prior to the lane change task. Not to mention that a typical engine does not generate special sound signals indicating which phase the vehicle is in during a bi-phasic lane change manoeuvre. Second, the influence of force-feedback from steering wheel is likely not the source since an experiment was conducted to address it (see Study 1, Expt.

1). Thirdly, other cues such as body movements and proprioception may indeed contribute. But body movements were also generated by inertial feedback and it may be integrated with vestibular cues in the brain. For example, when vestibular system senses a leftward acceleration, a push from seatbelt could reinforce such sensation. That is, vestibular cues and corresponding body movements can be seen as one system since it is very difficult to separate them in a real-world test. In addition, there is no reported reliable way to separate signals from proprioception and vestibular system. Due to that this study, and many others, could only control and measure vestibular inputs quantitatively, we consider vestibular cues as the major factor in this experiment. Nonetheless, we do not rule out the possibility that proprioception is likely to participate.

We would suggest that future research should focus on investigating on how visual feedback is integrated with vestibular cues in the brain. By combining mobile simulator technology with real vehicle steering, we believe such a combination will offer a powerful approach for studying the interplay of these cues, one which circumvents shortcomings in our current ability to simulate the entire gamut of non-visual (vestibular and somatosensory) cues in the laboratory. On the other hand, we also encourage future research to further investigate what quality of signal is required from the vestibular system, e.g. does it have to be directional signal above a certain threshold, or would jerks during steering suffice? A recent study done by Cheng and Gu (2016) may shed light on this topic. They found that it is the curvilinear motion (translation with rotation) that significantly activates the vestibular system, compared with translation or rotation only.

Conclusion

The results strongly suggest that non-visual information experienced during active steering is incorporated in the control of self-locomotion. For the first time, we show that vestibular cues are likely to participate in real-world lane changing behavior. We believe our results should prompt theoreticians to include non-visual senses (e.g. vestibular cues) into their models of control and cautions against over-interpreting results from simulator studies in which these cues are either weak, non-existent and invariably conflicted.

Appendix Supplementary Data for The Real Vehicle Experiment

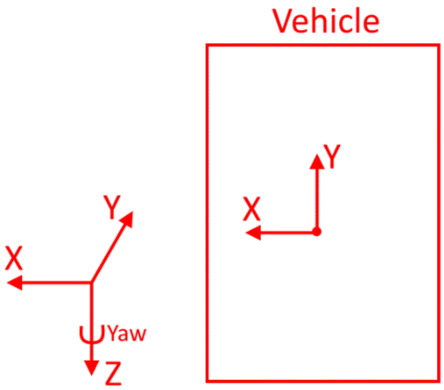

Figure 1 illustrates the three axes defined by the accelerometer.

Some supplementary data was provided to show the average speed, acceleration, and yaw rate of the vehicle. Figure 1 demonstrates the three primary axes defined by the accelerometer. It is necessary to define the time period of lane change manoeuvre before providing more data, since participants completed the task within different time in different trials. The average time needed for participants to complete the task was 6.58 (M) ± 1.40 (SD) seconds. The average speed, acceleration, and yaw rate were analysed for the duration of M + SD = 7.98 seconds. If some participants completed the manoeuvre before that duration, then the average was calculated based on the rest of participants. As a consequence, after the mean duration (6.58s) the results might be biased toward those remaining participants. Figure 2 shows the average speed for lane change in both conditions. We intentionally aimed at 45 km/h during lane change due to safety reason. Figure 3 shows the acceleration (unit is G) along X-Axis (i.e. the roll acceleration in some literatures) in no visual feedback condition. This acceleration was mainly caused by yaw due to vehicle dynamics, hence it is connected to the yaw rate (see Figure 5a and Figure 5b in the main body for typical individual yaw rate, see Figure 4 in this Appendix for average yaw rate). The roll acceleration in visual feedback condition is not explicitly shown here because basically it was the same to Figure 3. The average peak roll acceleration during lane change in no visual feedback condition shown in Figure 3 was at least around ±0.1g (see Figure 3), similar to Gu, DeAngelis et al's study (Gu, DeAngelis et al. 2007). Nonetheless, because participants might experience peak roll acceleration at different time point, the average data shown in Figure 3 are very conservative. We further obtained individual peak roll acceleration (in no visual feedback condition only) and calculated mean peak roll acceleration based on those individual data (in no visual feedback condition only). The results show that, on average, the peak roll acceleration experienced by participants during lane change in no visual feedback condition were 0.183g (M) ± 0.062g (SD) and -0.216g (M) ± 0.040g (SD). Since no literature explicitly demonstrates the relation between the perception threshold of an acceleration profile and the duration exposed to that acceleration, we also calculated the mean time period participants were exposed to the roll acceleration above ± 0.1g (in no visual feedback condition only). The results show that, on average, the duration was 0.218s (M) ± 0.142s (SD) and 0.376s (M) ± 0.198s (SD), in which participants experienced the roll acceleration above +0.1g and -0.1g, respectively, during lane change in no visual feedback condition.

As a complement, average yaw rate over participants in no visual feedback condition is also shown in Figure 4. The yaw profiles in visual feedback condition is essentially similar to Figure 4 so it is not explicitly shown here. Note that the roll acceleration and the yaw rate is disconnected after time = 6s on the x-axis, this is because averagely the vehicle was braked since that time point (see Figure 2). The brake caused additional roll acceleration onto the vehicle (as it does not ideally just linearly deaccelerate the vehicle).

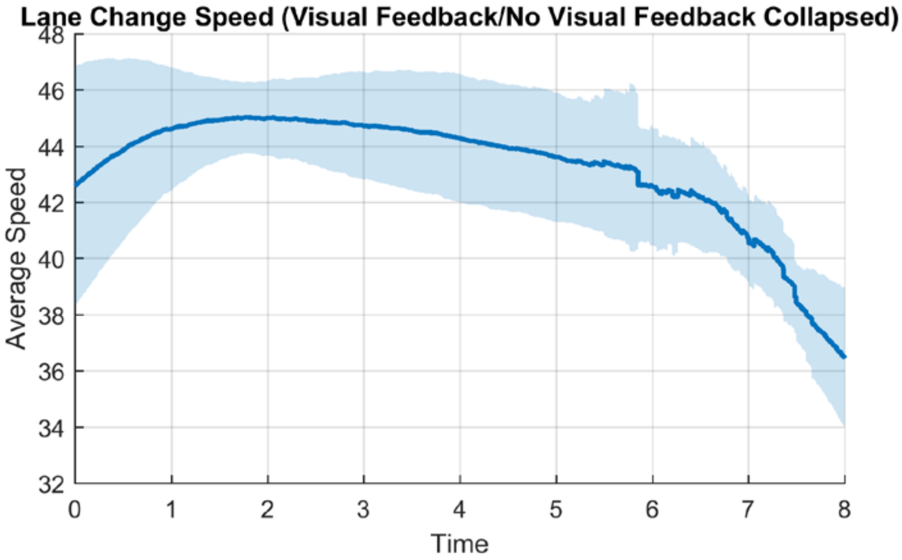

Figure 2 shows the average speed (around 45 km/h) during the entire lane change duration. Shades indicate the standard deviation.

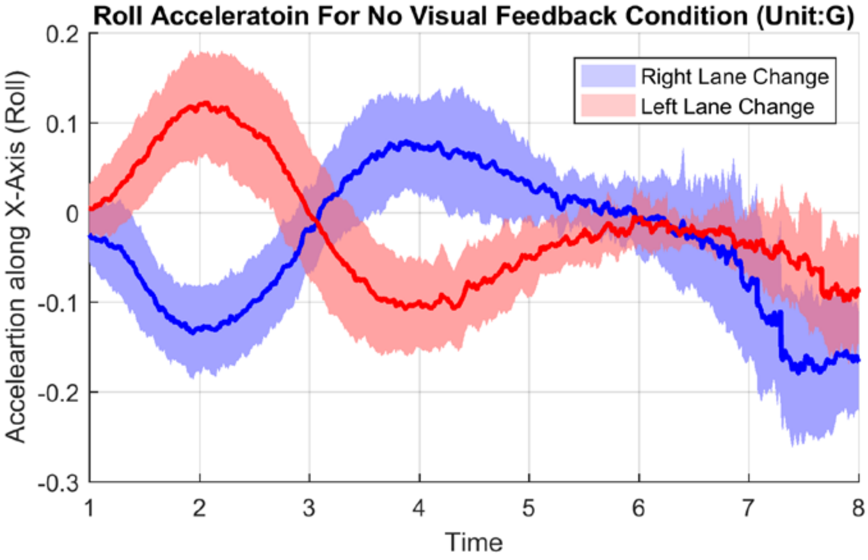

Figure 3 shows the acceleration along X-Axis (roll acceleration) during lane change manoeuvre in no visual feedback condition. Quite conservatively, the average peak acceleration was at least above 0.1g. Shades indicate the standard deviation.

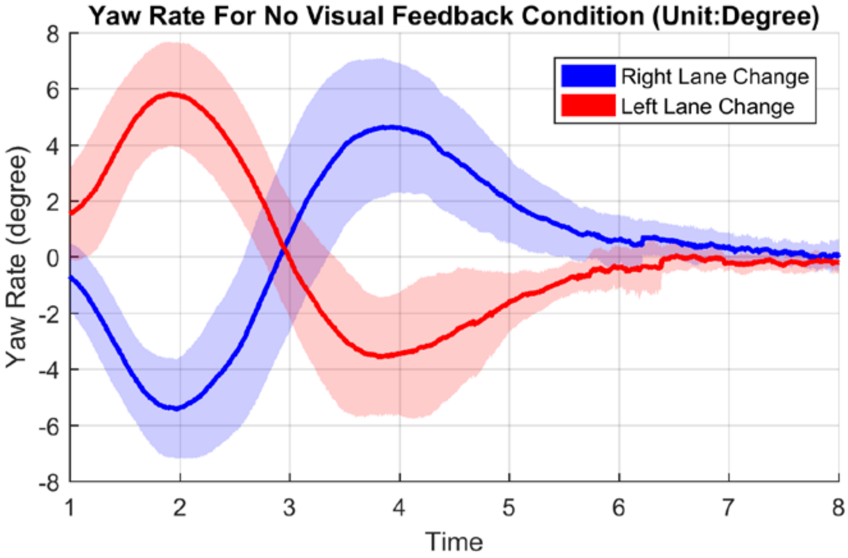

Figure 4 shows the average yaw rate across participants during lane changing in no visual feedback condition. It is clear that on average participants produced a return phase. Shades indicate the standard deviation.

Chapter Six - Discussion

Summary

Three studies had been conducted to investigate steering, particular lane change, under various circumstances. We found that the trait of a steering wheel re-centring itself does not influence drivers' lane change behaviour (Study 1). People intend to carry out a uni-phasic manoeuvre instead of a required bi-phasic manoeuvre during lane change, regardless of the type of road (i.e. straight or circular) and simulators (i.e. fixed-based simulator or motion platform). The consistently erroneous behaviour seen in the absence of visual feedback led us to think that drivers may treat a steering wheel as a rate control device for lateral position (although it is, in fact, an acceleration/second-order control device for lateral position). The pilot experiment in Study 1 was carried out to test this assumption. In this experiment, we found that steering performance was indistinguishable between two control devices (i.e. rate control device vs. acceleration control device). The results suggest that participants were comfortable driving a vehicle fitted with a lateral control device. Overall, in Study 1 we propose that the representation of vehicle dynamics internalized by drivers is fundamentally wrong, consistent with earlier work from our group (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009, Xu, Wallis et al. 2014). We will further discuss topics related to a proposed internal model later in this chapter.

In Study 2, we tested lane changing behaviour in a range of optic flow fields. This is because if drivers' internal representation of vehicle dynamics is wrong, they would need certain visual cues to correct their internal model. The pilot experiment showed that drivers' steering strategies are tightly associated with the type of flow fields (i.e. no optic flow, plain environment, normal road texture). With sufficient information available, drivers prefer to approach a narrow opening (gate) 'head-on' which in our task required them to complete a two-phase steering movement between gates. Interestingly, a relatively featureless texture plain was insufficient to support this approach despite supplying sufficient information for drivers to estimate their instantaneous heading. On the basis of this finding, we conducted a second experiment to further investigate lane change in flow fields. First, a classic "heading discrimination" experiment confirmed that participants could perceive heading accurately with our stimulus and apparatus. We then asked participants to carry out a lane change in various optic flow fields. Surprisingly, despite the accurate heading perception, they still made the same consistent, systematic mistake (i.e. the lack of a return phase) during lane change in all flow fields. Given the results, we conclude that bi-phasic steering tasks typified by lane changing require more than optic flow fields (e.g. fixations on an outstanding feature). We discuss the role of visual cues in steering below.

In Study 3, we extended our experiments into an alternative, but related manoeuvre using the latest VR technology, to focus on “parallel parking”, using an Oculus Rift DK2. Both paralleling parking and lane changing require a bi-phasic manoeuvre, but drivers may treat them differently. Paralleling parking is often considered a demanding unintuitive manoeuvre, in contrast of lane changing. Interestingly, on average participants achieved reasonably good performance in parallel parking with no visual feedback. They also achieved on average good performance in an unusual setting of “reverse” lane changing. Although some methodological limitations mean we must be guarded about how much we can conclude from these preliminary studies, there is some tantalising evidence that the naive steering behaviour seen when driving forwards disappears when driving backwards (most especially in the case of parking).

In Study 4 we conducted a lane change experiment in a real vehicle. Surprisingly, the results show that although participants failed to conduct a lane change in a fixed-base simulator with no visual feedback, they were able to produce a lane change in a real vehicle. Consequently, the results strongly suggest that full, natural inertial feedback provided by a real vehicle forms an integral component to daily steering tasks. The role of vestibular information in steering will be discussed below.

Internal Model of Steering

In Study 1, we confirmed previous findings that drivers appear unable to correctly predict the outcome of their steering movements when carrying out everyday tasks such as lane following and lane changing (Cloete and Wallis 2009). On the basis of such results one might ask whether drivers actually operate an internal model at all, since an incorrect model is likely to be, at best useless, or at worst actually interferes with successful execution. To answer this, it is important to look to the literature on reaching and interception tasks, where the existence of internal models is widely accepted (for reviews see (Kawato 1999, Zago, McIntyre et al. 2008, Shadmehr, Smith et al. 2010, Zhao and Warren 2015)). In studies investigating catching a free-falling object, for example, researchers have found that humans appear to use an internal model to estimate linear acceleration, such as that due to earth’s gravity (Kawato 1999, Merfeld, Zupan et al. 1999, Snyder 1999, Shadmehr, Smith et al. 2010). Arm reaching studies involving force fields have found that humans can gradually adapt to imposed external dynamics (e.g. robotic arm) and still hit the target in a visually perceived straight path (e.g.(Sainburg, Ghez et al. 1999)). In visuomotor rotation experiments, humans appear able to easily adapt to different rotations (e.g. (Flanagan and Rao 1995)). Further, the adaptation even persists after the removal of force field or rotation, strongly implying a new representation of the external world is stored. Taken together, various studies have found evidence favouring adaptive internal models in the brain. Interestingly, adaption is also confirmed in self-locomotion studies. Bruggeman, Zosh et al. (2007) and Saunders and Durgin (2011) found that during exposure to flow fields in which the focus of expansion is disconnected from egocentric direction or physical heading, people show progressive adaptation. The adaptation also persists after the removal of the imposed bias, implying lasting adaptation to the new dynamics.

In driving, the situation is complicated by its relatively long duration and the associated importance of forward planning. Lehtonen, Lappi et al. (2014) found that experienced drivers invest a considerable amount of mental resources on “trajectory planning” (feed-forward control) during steering. Open-loop “trajectory planning” does not need to be absolutely correct to be effective. Nash, Cole et al. (2016) describe a steering model in which steering was largely controlled in a feed-forward manner. Although errors were generated by the model (due to an imperfect internal model, sensory error/delay, and/or other sources of noise) the model appeared to capture real-world human behaviour. In particular, they stated that in their model “the feedback of vehicle motion is not used directly for generating the feed-forward control actions; however, the feedback loop is able to correct for any discrepancies introduced by imperfections in the driver’s feedforward control”. Clearly, an imperfect feedforward control still helps in steering. Wallis, Chatziastros et al. (2007) showed that a correct lane change can be restored using brief (i.e. 100ms) visual feedback at crucial time points (i.e. at the beginning of each steering phase), implying that with very limited but suitably timed visual feedback, steering can be guided by a feed-forward control loop.

One of the surprising outcome of this work is that apart from visual feedback, Study 4 found that vestibular cues too are sufficient for producing a roughly accurate lane change. As briefly described above, vestibular systems are thought to be tightly associated with acceleration systems, for example the earth gravity (McIntyre, Zago et al. 2001, Zago and Lacquaniti 2005). Since the modern steering wheel is essentially an acceleration control device for lateral position, drivers may develop an implicitly correct representation of vehicle dynamics associated with vestibular cues. Such an implicit model does not have to exist in an analytical, mathematical form, rather, it can be approximate, probabilistic knowledge (Zago, McIntyre et al. 2008). This hypothesis explains why drivers demonstrate an on average correct bi-phasic manoeuvre during lane change when vestibular cues are present but only a uni-phasic manoeuvre when vestibular cues are absent. Some neurophysiological studies have also demonstrated fMRI evidence that internal models relating to acceleration may exist in vestibular cortex (Merfeld, Zupan et al. 1999, Snyder 1999, Indovina, Maffei et al. 2005).

An alternative to the full internal model, is a prospective control model relying on online information. Proponents of this approach argue that a predicative control model (i.e. internal model) is uneconomic for the brain to incorporate since online information is sufficient for a wide range of tasks (Baures, Benguigui et al. 2007, Zhao and Warren 2015). Zhao and Warren suggest that a simple heuristic, mapping strategy can be used to explain much of the studies claiming to support an internal model (e.g. catching a freefalling ball, visuomotor rotation, etc.). They propose that through repeated trials in those experiments, a mapping can be established for a particular task, e.g. participants memorised the intercepting position of the falling object through repeated trials. In a related vein, Bayesian models have successfully been applied to the task of acquiring an ability to cope with acceleration when catching a falling object (Franklin and Wolpert 2011). In this respect, not only is a model of gravity is unnecessary, but also the memory of the exact gravitational constant becomes redundant. Zhao and Warren have suggested that humans can use a narrow-context heuristic strategy such as constant bearing angle relying on online optical information to guide self-locomotion, without involvement of an internal model. Consistent with this proposal, Andersen and Sauer (2007) suggest that car-following steering can be modelled using visual angle to the lead vehicle alone, excluding the need for an internal model of vehicle dynamics.

The main problem with all of these discussions is that it can be difficult to distinguish predictions of an internal model from a heuristic, mapping strategy, since there is no board agreement on the definition of each concept. Zhao and Warrant suggest that a mapping strategy can be regarded as a piece of memory storing a constant or a simple mapping relation, whereas an internal model should exist in an explicit form that takes variables and hence can be generalized to other similar scenarios. From this perspective, constant bearing angle, visual angle, focus of expansion, and implicit, approximate gravity knowledge such as gravitational constant should all fall into a heuristic, mapping strategy, whereas the representation of vehicle dynamics belongs to internal model. That said, to design an experiment to distinguish the two is not easy. In terms of Study 1 and Study 4, one can argue that an internal model of lane change is associated with vestibular systems. But it is also possible that drivers may simply expect two “pushes” from the seatbelt during lane change --- two “pushes” equal to two peak roll acceleration in opposite direction during a typical lane change. In the latter, a representation of vehicle dynamics is unnecessary. Perhaps a test of generality would help, as Zhao and Warren suggest. Since a mapping strategy does not take variables but internal model does, one could expect the same pattern of behaviour can be generalized if it is motivated by an internal model. In this case, earlier lane changing study and obstacle-avoidance study from our group (Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Cloete and Wallis 2009) may shed light on this issue. In those studies, the same pattern of steering error was found across lane change and obstacle avoidance.

Future studies should continue to work on exploring methods able to distinguish between internal models and a heuristic, mapping strategy. It would be beneficial to address to what extent an internal model or mapping strategy contributes to steering and how it integrates with online sensory information. Of course, in practical terms resolution of this debate may not always matter. Driver training programs can incorporate the latest findings in motor learning, such as instances under which an implicit strategy can override an explicit plan as described in visuomotor rotation studies (Mazzoni and Krakauer 2006). This phenomenon emphasizes that explicitly learned strategies may help in the very beginning of a task, but implicit plans may affect that task in the longer term. Hence for some risky steering manoeuvres, extensive training in the real world may be needed.

Visual Cues for Steering

In Study 2, we demonstrated that although optic flow supports accurate heading estimation, it is insufficient for a lane change manoeuvre. This appears at odds with the common assumption that a velocity field of this kind is capable of providing sufficient visual cues to regulate steering (Gibson 1950, Gibson 1958, Warren and Hannon 1988, Warren, Kay et al. 2001, Li and Warren 2002, Li, Stone et al. 2011). Our results therefore reflect a line of thinking in the literature questioning whether accurate heading perception is either necessary or sufficient for accurate steering performance. In a typical heading discrimination task, participants passively perceive the movement of flow fields and compare the simulated heading direction to a reference point. Their performance is then defined as a selected point of a fitted psychometric function, e.g. a point along the function where participants reach 75% correct. However, researchers have argued that this common method lacks ecological validity, hence should not be regarded as a reflection of what humans are actually doing during self-locomotion (Wilkie and Wann 2006). Indeed, it has been argued that the popular threshold of 75% correct may be too risky in high speed steering, in which a small heading deviation can soon lead to an accident. One solution is to increase the % correct, e.g. from 75% correct to 90% or higher. Nonetheless, due to the characteristic of the psychometric function, an increase in % correct will cause the threshold to increase exponentially (see (Wann and Land 2000)). Thus, it is questionable whether the threshold derived from a psychometric function could underlie a practicable strategy for the control of self-locomotion.

Another problem with the use of heading data is that the although typical heading discrimination tasks produce thresholds close to 1^o to 2^o, a “heading locating” task (pointing towards the direction of heading) can yield results twice as large (Kountouriotis and Wilkie 2013). Some authors argue that this gap can be largely attributed to the vicissitudes of memory in the “heading locating” task (Cutting, Vishton et al. 1997). However, the presentation of a reference point in the heading discrimination task may help achieve better performance (Van den Berg 1996). Van den Berg found his participants achieved significantly better performance if they judged heading relative to a fixation point, rather than judging from the entire motion pattern of the flow field. Taken together, the inconsistency among heading perception studies and the potential use of the reference point in heading discrimination tasks questions the justification of directly applying results from those studies to self-locomotion control strategies.

Quite apart from these criticisms of the flow literature, it is important to emphasise that heading perception is often a passive task whereas self-motion is an active task. Previous studies have shown that passive tasks are quite different from active tasks in terms of brain activities and perception of sensory information. Flach (1990) addressed the difference on control models between being an actor and being an observer, see also (Nash, Cole et al. 2016). Through fMRI studies, Walter, Vetter et al. (2001) detected numerous differences between active and passive driving (i.e. passengers). Apart from self-locomotion, it has also been reported that carry-over effects after visuomotor adaption only occur in participants who actively move their hands (for a review, see (Shadmehr, Smith et al. 2010)).

As this discussion edges towards an alternative to flow-based control, it’s perhaps informative to reflect on studies that have aimed to study flow in the past. In practice, many of these studies incorporated egocentric direction either explicitly or implicitly, since they often required participants to steer towards a target or had an outstanding feature for participants to fixate (e.g. (Warren, Kay et al. 2001, Li and Warren 2002, Wilkie and Wann

2002, Wilkie and Wann 2003, Li and Warren 2004, Li, Stone et al. 2008, Li and Cheng 2011a, Kountouriotis and Wilkie 2013)). Hence when Wann, Land, Wilkie propose a model emphasising the contribution of visual direction to the target (or a point along future path) during steering it is not at odds with one interpretation of these previous studies (Wann and Land 2000, Wann and Swapp 2000, Wilkie and Wann 2002, Wilkie and Wann 2003, Wilkie and Wann 2006, Wilkie, Wann et al. 2008, Wilkie, Kountouriotis et al. 2010). Further, some less-generalized steering strategies too incorporate egocentric direction, e.g. fixating on a landmark feature, the tangent point, during curve negotiation (Land and Lee 1994), or measuring visual angle to the lead vehicle during car following (Andersen and Sauer 2007). Taken together, these steering models all point to the fact that successful control of steering requires visual direction cues. As such, one can consider alternative theories that employs fixations for the control of steering to account for the results of Study 2.

One candidate model is the future path strategy (FP) proposed by Wann and colleagues (Wann and Land 2000, Wann and Swapp 2000, Wilkie and Wann 2002, Wilkie and Wann 2003, Wilkie and Wann 2006, Wilkie, Wann et al. 2008, Wilkie, Kountouriotis et al. 2010). FP suggests that humans can fixate an area 1 to 2 seconds ahead and that the streamers along the future path towards that fixation will guide steering. In theory, it is possible for drivers to continuously switch fixations to make a lane change, e.g. gradually switch fixation from the current lane to the destination lane. By continuously steering towards this virtual target a lane change is produced. Another similar and widely accepted model, the “two-point” steering strategy, employs gaze towards two areas for steering, with one closer to the vehicle and one farther away (Donges 1978, Land and Horwood 1995, Salvucci and Gray 2004). The “two-point” steering strategy systematically describes how a lane change can be achieved by using gazes --- that is, by setting both near target and far target to the destination lane. Salvucci and Gray claimed that their computer-simulated lane change trajectories based on the “two-point” strategy were consistent with their real human data (Salvucci and Liu 2002, Salvucci and Gray 2004). The use of fixations or gaze towards certain areas would explain why participants failed in flow fields consisting of cloud of dots where tracking of targets becomes difficult to impossible. It can also account for the small improvement seen in the ground plane in Study 2. That said, the lane change performance on a ground plane is still far from perfect. We believe this could be due to the diffuse patterns we used which again hider accurate tracking of target locations. It is likely that humans cannot steadily fixate an indistinct feature in a cluttered environment due to visual crowding (Whitney and Levi 2011). In this case, even though FP and “two-point” strategy can guide steering, they may be obscured by the use of an isotropic texture with no outstanding feature. This hypothesis can also be used to understand previous work. Earlier studies have found that the addition of reference objects in flow fields significantly increase steering performance (Li and Warren 2000, Li and Warren 2002). Those reference objects were in fact ideal outstanding features. Li and Chen (2010) found splay angle, which is measured through fixations along a segment of road edge, is sufficient for a lane keeping task. Kountouriotis, Floyd et al. (2012) found that drivers intend to direct their gaze to the visible road edge during steering. Obviously, road edges offer one possible source of effective, successive fixation targets. With all this said, there are obviously other issues at work in determining optimal targets for fixation. A real-world study tested the roles of fixation location during cycling along different road surfaces (smooth, high quality surface vs. rough, low quality surface) (Vansteenkiste, Zeuwts et al. 2014). The authors found that shifting fixations towards proximate road properties helped cyclists maintain the desired riding speed on a rough surface. As a result, the authors pointed out that the popular “two-point” steering strategy is probably too simplistic when considered in a real-world environment because “it does not take into account the influence of environmental factors on the gaze behaviour”.

Future work should focus on exploring what type of fixation is required for steering. For instance, one can manipulate the quality and quantity of fixation targets available during steering. It would also be of interest to explore how optic flow and fixations are used together to guide steering.

Steering Beyond Visual Cues

Extra-retinal information such as eye movement signals have long been shown to be essential for the guidance of self-locomotion (Royden, Banks et al. 1992, Royden, Crowell et al. 1994, Banks, Ehrlich et al. 1996, Ehrlich, Beck et al. 1998, Li and Warren 2000, Li and Warren 2002, Saunders and Niehorster 2010). The role of other non-retinal cues such as vestibular information had been less clear. However, more recently Gu, DeAngelis et al. (2007) found that vestibular cues are sufficient for accurate heading perception and that these cues are integrated with visual feedback (Gu, DeAngelis et al. 2007, Gu, Angelaki et al. 2008, Fetsch, Turner et al. 2009, Butler, Smith et al. 2010). Consistent with those studies, Study 4 reports that vestibular cues contribute in daily steering activities typified by lane change. Apart from this finding, in Study 4 we also discovered another important trait of vestibular cues --- the importance of presentation of both translation and rotation. The vestibular system has three semicircular canals for detecting rotation and two otolith organs for sensing translational acceleration (for a comprehensive review see (Angelaki and Cullen 2008)). It is not clear how each type of movement contributes to human navigation systems, but it seems in certain situations both cues are needed. A recent study has found that certain neurons in the primate (i.e. monkeys) cortex have the largest response for curvilinear motion with both translation and rotation (Cheng and Gu 2016). In Study 4, where a real vehicle and a large test ground were used, the results clearly indicate that participants significantly changed their steering behaviour --- that they conducted a largely accurate lane change manoeuvre. Such performance in lane change have not been seen in studies using a fixed-base simulator or a motion platform ((Wallis, Chatziastros et al. 2002, Wallis, Chatziastros et al. 2007, Xu, Wallis et al. 2014), see also Study 1). Importantly, the motion platform lacked translational movement. Not to mention it could not offer a combination of translation and rotation. This discrepancy between motion platform and real vehicle reveals that drivers may expect a translational component during steering. On the other hand, the lack of linear acceleration of the motion platform also created an unnatural situation --- a modern vehicle cannot be turned while it is not moving forward.

Currently, there is an increasing trend to investigate how vestibular cues are integrated with visual feedback. Some studies have found that the vestibular system is weighted higher than visual cues in perceiving passively travelled distance (Harris, Jenkin et al. 2000, Bertin and Berthoz 2004). Harris et al. attributed this phenomenon to a biological reason that it is safer to over-react to unexpected passive movement. Some studies have found that vestibular systems may participate in precise heading control tasks (Gu, DeAngelis et al. 2007, Gu, Angelaki et al. 2008). Gu et al. found that in heading discrimination tasks with passive vestibular cues alone (i.e. subjects being passively moved in a dark environment), primates can achieve a level of performance that is as good as they do with full visual feedback. This performance shows significant improvement over previous studies (Telford, Howard et al. 1995) and (Ohmi 1996), in both of which heading judgements based on vestibular alone were very poor. This discrepancy can be explained by the different methodologies used (heading discrimination vs. heading locating). Nonetheless, it is worth mentioning that Telford, Ohmi, et al. used low acceleration profiles (0.05g), whereas Gu et al. used 0.1g. A precise perception based on vestibular systems may require a reasonable high acceleration. In Study 4, despite not being able to control the output of acceleration we did found that on average participants experienced a peak acceleration around 0.2g. More recently, follow-up studies generally suggest that the integration of vestibular information and visual cues is in a statistically optimal fashion (Fetsch, Turner et al. 2009, Butler, Smith et al. 2010, Campos, Byrne et al. 2010, Fetsch, Pouget et al. 2012, Saunders 2014, Butler, Campos et al. 2015). From a neurophysiological perspective, evidence favouring a statistically optimal integration of vestibular cues and visual feedback in the brain emerged from recent studies (Gu, DeAngelis et al. 2007, Gu, Angelaki et al. 2008, Fetsch, Pouget et al. 2012). That said, de Winkel, Weesie et al. (2010) found their results could not be captured by a Maximum Likelihood Integration, implying the statistically optimal integration does not always hold. But an overestimation on vestibular cues is again confirmed by their work. Taken together, those findings challenge the common assumption that visual feedback dominates in self-locomotion. Nonetheless, it is worth mentioning that the relative emphasis placed on vestibular cues are mainly found by studies involving passive motion. By contrast, Saunders (2014) conducted a study using active indoor walking and no over emphasis of vestibular feedback was found. This difference can be explained by the different methodology, but perhaps, as Harris et al. suggest, humans may overreact to unexpected passive motion. Apart from this finding, Saunders also found that optic flow has a weaker influence in guiding walking than commonly assumed. He stated that “unless optic flow provided very strong information, an optimal strategy would rely primarily on feed-forward predication and nonvisual sensory information”. To some extent, his conclusion is consistent with our current findings. We have proposed that feed-forward control and vestibular cues are incorporated in steering and optic flow alone cannot support accurate steering.

Future work should investigate how vestibular cues and visual feedback are integrated during steering. Despite the increasing literatures on this topic, a number of questions remain to be answered. Can a simulated combination of translation and rotation, such as a small turning radius that can be fitted in a room, motivate similar steering behaviour shown in Study 4? As an active self-locomotion task, do drivers overestimate vestibular cues during steering?

And lastly, given the significantly different results observed between simulator studies and a real-vehicle study, we urge theoreticians to include non-visual senses (e.g. vestibular cues) in their models of control and caution against over-interpreting results from simulator studies in which these cues are either weak or absent and invariably in conflict with visual stimulation received.

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