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The role of gaze and road edge information during high-speed locomotion

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Abstract

Robust control of skilled actions requires the flexible combination of multiple sources of information. Here we examined the role of gaze during high-speed locomotor steering and in particular the role of feedback from the visible road edges. Participants were required to maintain one of three lateral positions on the road when one or both edges were degraded (either by fading or removing them). Steering became increasingly impaired as road edge information was degraded, with gaze being predominantly directed towards the required road position. When either of the road edges were removed, we observed systematic shifts in steering and gaze direction dependent upon both the required road position and the visible edge. A second experiment required fixation on the road center or beyond the road edges. The results showed that the direction of gaze led to predictable steering biases, which increased as road edge information became degraded. A new steering model demonstrates that the direction of gaze and both road edges influence steering in a manner consistent with the flexible weighted combination of near road feedback information and prospective gaze information.

1 Introduction

Human control over skilled actions is remarkably robust. We interact with the world successfully despite dealing with constant fluctuations in the quantity and quality of information available to our perceptual motor system. Because we act upon the world under a wide range of conditions it seems that we often use a flexible weighted combination of information. This means that reliable information contributes proportionally more toward the control of action than unreliable signals. Such flexible weighting has been found in discrete actions such as grasping an object (Ernst & Banks, 2002) but also during the continuous online control of action, e.g. steering towards a single target (Wilkie & Wann, 2002).

Generating visually driven actions that avoid collision is a regular requirement for our perceptual-motor system e.g. reaching between/around obstacles, walking along a path or down a corridor, or driving along a road. In any of these tasks actions can be generated on the basis of a pre-planned set of commands (open loop control) or by using sensory feedback to adjust actions (closed loop control). Consider first the case of reaching past an obstacle using only visual feedback to avoid collision: if the gap between the hand and the obstacle reduces at a rapid rate then a collision is likely and so the hand should be moved so the gap increases. Using feedback in this way is likely to result in slow and/or jerky movements because the consequence of each movement needs to be evaluated before further movement can take place. Acting solely on the basis of feedback information could be implemented by carrying out a series of stepped actions, or by generating a continuous action that is sufficiently slow to allow time for feedback to inform alterations to the trajectory. Use of feedback might be a useful strategy when grasping a fragile object, or reversing your car into a tight parking spot, but not for generating smooth, fast actions. Consider instead the case of reaching to pick up a mug on an uncluttered desk. The initial reach to get the hand close to the mug is relatively unconstrained and could be achieved by moving the arm through a variety of trajectories quickly without fear of collision. The grasp phase, however, requires precise control over the hand and fingers to avoid an unexpected collision with the mug and to ensure that contact occurs at an appropriate location with sufficient force for lifting. It might be expected, therefore, that the initial reach phase is largely driven by feedforward mechanisms, with feedback playing a greater role during the grasp phase. Indeed, because of delays in sensorimotor loops it has been proposed that reaching movements are largely pre-programmed with sensory feedback only influencing the end of the trajectory (Keele, 1968; Hollerbach, 1982). There are a number of studies, however, that have shown that sensory feedback has a critical role in updating forward models and so the human system seems to combine feedback and feedforward components throughout the trajectory to generate smooth, rapid actions (see Desmurget & Grafton, 2000, for a review).

It can be difficult to fully quantify the combination of feedback and feedforward information in tasks such as reaching to grasp an object or steering to a single target because of the potential change in utility of information as the goal is approached (i.e. it is easier to realize you are on the wrong trajectory as you get closer to an object). One of the benefits of examining the control of actions within a clearly bounded region (e.g. steering between road edges) is that feedback remains broadly equivalent throughout the trajectory with no single static goal that is approached. Steering along delineated paths is a common human behavior, and it seems likely that the mechanisms that support running along a forest path, also generalize to cycling the Alps in the Tour de France, or driving down a country lane (Field, Wilkie, & Wann, 2007). Some of the most influential steering models (e.g. Donges, 1978; Salvucci & Gray, 2004) propose that a driver is guided along a roadway using two regions that partially map onto feedback and feedforward components: i) a point located near the driver for maintaining the desired lateral position on the road, and ii) a far point that facilitates matching the upcoming curvature of the road. This distinction is supported by the findings of Land and Horwood (1995) who manipulated the visibility of near and far roadway segments. They found that removing the near road segment resulted in smooth steering but caused errors relative to the road. In contrast, when the far road segment was missing, participants maintained their position in lane much better, but no longer steered as smoothly. Whilst there is recent evidence that indicates these findings may be caused by limitations in stimulus refresh rates (Cloete & Wallis, 2011), it remains the case that near-road information could provide a useful error feedback signal, whereas the far-road could be used to indicate the upcoming curvature of the road.

Where we look when we steer

Skilled actions seem to require specific spatiotemporal oculomotor strategies for sampling information useful for the task in hand (Land & Furneaux, 1997). When reaching to pick up an object it is natural to look at the object rather than the hand (Land & Hayhoe, 2001) and when performing bimanual reaching, gaze alternates between the objects to be grasped (Bingham, Hughes, & Mon-Williams, 2008). Similarities can be drawn between bimanual reaching and steering through a series of waypoints (e.g. a slalom) where the most immediate target is tracked until it is 1–2 s ahead, at which point gaze is directed to the next steering target in the sequence (Wilkie, Wann, & Allison, 2008). When carrying out an action within a demarked zone, useful information becomes distributed across the scene so it is less obvious where (and when) the actor needs to look to be successful. Real-world studies suggest that looking toward the inside edge of the bend provides useful information for steering (Kandil, Rotter, & Lappe, 2009; Land & Lee, 1994). Land and Lee (1994) observed the behavior of a small number of drivers steering around a bending roadway and noted extensive fixation of the tangent point, an optical feature at the apex of the inside road edge. They proposed that fixation of this point provides the driver with information about the upcoming curvature of the bend. Whilst this is an attractive and elegant solution to steering around a bending road, there are a number of problems with relying on a single feature in this way. Wilkie, Kountouriotis, Merat, and Wann (2010) outline several issues with using the tangent point, with the crucial criticism being the lack of generalization to steering in an open field setting or conditions where the tangent point is obscured. Even when the tangent point is available it is not clear that fixating it improves steering. Robertshaw and Wilkie (2008) found no advantage in fixating the tangent point, and Mars (2008) concluded that there was less stable steering when fixating the tangent point compared to other road regions (but see Kandil et al., 2009, for a contrasting view). Because Mars (2008) used multiple lanes separated by a broken line, degraded lane information may have removed some useful property of the tangent point on half of the bends. Land and Horwood (1995) found that when the tangent point was not available drivers were still able to steer, and while steering was less smooth it is unclear whether this was solely due to removal of the tangent point since part of the outside road edge was also removed.

An alternative model of using gaze to control steering has been put forward by Wilkie and Wann (2002, 2003a). They propose that drivers look at the point they want to pass through, usually 1–2 seconds ahead of their current position. Tracking this point for short periods provides information in a form that should be useful for steering. Wilkie et al. (2008) expanded the initial conception of the 'active gaze' model to demonstrate how a number of visual and non-visual angular and rotation estimates can act as a point attractor for the steering trajectory[1]. Not only can this be used to model steering in an open field setting, but it can explain the large proportion of fixations on and around the tangent point reported in some real-world driving studies (Kandil et al., 2009; Land & Lee, 1994). Indeed, Wilkie et al. (2010) showed that participants only looked towards the tangent point when they were steering a racing-line that approached the inside road edge. The initial conception of the active gaze model did not incorporate visual feedback from road edges, relying predominantly on prospective gaze fixations to supply the necessary information. It is clear, however, that steering can be influenced by peripheral visual feedback information: Wilkie et al. (2008) demonstrated that when steering through a series of waypoints having a peripheral view of steering targets was often important for accurate steering, and Robertshaw & Wilkie (2008) showed that a peripheral view of road edges seems to provide a powerful source of error feedback. What remains unclear is whether a single boundary is sufficient to supply useful feedback information for skilled visual-motor control and the degree to which prospective gaze information influences action when this feedback is available.

Where we steer when we look: steering with offset gaze

During high-speed locomotor steering there is a tight coupling between gaze (head and eye) inputs and steering outputs (Land & Lee, 1994; Land & Tatler, 2001; Wilkie & Wann, 2003b). Whilst this coupling usually aids motor actions, it does seem that it can also lead to directional steering biases when gaze is held eccentric to the required trajectory (Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Robertshaw & Wilkie, 2008). Readinger et al. (2002) carried out a series of experiments that examined whether fixating an eccentric target influenced steering when maintaining a straight trajectory along a simulated roadway. They found a reliable bias toward the point of fixation at the beginning of trials which was generally proportional to the degree of gaze eccentricity. In a clever manipulation they reversed the steering wheel mapping (so a clockwise turn steered in an anticlockwise direction and vice versa) and found identical biases. This ruled out biomechanical or physiological explanations for the bias since participants still steered in the direction of fixation (despite moving their hands in the opposite direction). Throughout trials participants tended to perform a series of steering corrections to avoid leaving the road, which is consistent with the use of both prospective gaze information (which caused drift) and feedback from road edges (which informed the corrections). Whilst Readinger et al. (2002) demonstrated that gaze can influence steering, the task was limited to maintaining heading on a straight line trajectory, rather than the more general case of steering curved paths. Whilst both are common locomotor scenarios, the steering requirements are somewhat different. To maintain a straight path merely requires the driver to monitor and nullify drift towards a road edge. This can be fulfilled by merely using feedback from near road information, with both edges providing similar information. In contrast, on a bending roadway, the inside and outside road edges are optically quite different (the inside edge has a clear apex - the tangent

[1]The original conception of using a point-attractor model within a locomotor control setting was put forward by Fajen and Warren (2003). They make an important case for treating steering as a dynamical system, but without specifying the information that is necessary to steer down a road, nor the route by which information is sampled from the environment (i.e. whether particular gaze behaviors are necessary in order to steer).

point) and to steer a smooth course may require the use of prospective information about future road curvature in addition to feedback from road edges. Robertshaw & Wilkie (2008) found that eccentric fixations did bias steering in a systematic fashion when steering bends, but only on wider roads. They suggested that when peripheral feedback information from road edges was weak gaze direction had greater influence over steering. Because the optical properties of roads change as they become wider it is difficult to directly compare performance on narrow and wide roads. Whilst altered optical properties are unlikely to explain the pattern of results, the steering patterns could be due to a simple propensity to cut corners on wider roads unless fixating unfamiliar regions of the road (i.e. the outside of the bend).

To investigate whether the human nervous system makes use of a weighted combination of prospective information (via gaze) and feedback information (from both boundary edges) we ran two new experiments. We asked participants to maintain a constant trajectory at one of three possible road positions (similar to Wilkie et al., 2010). We then systematically varied the quality of the inside and/or outside road edges to determine whether steering and/or gaze behavior changed, based on the proximity to the degraded edge. The tangent point model of steering merely requires fixation of the tangent point (and the known distance to the inside road edge; Land & Lee, 1994) to provide prospective information. No explicit feedback signal from road edges is used apart the information supplied by fixating the tangent point of the inside road edge. Based on this model there would be no reason to expect steering to be altered by maintaining different lateral road positions or for there to be any effect of degrading the outside road edge. Previous research would also suggest that ~80% of gaze fixations should fall on or around the tangent point (Land & Lee, 1994; Kandil et al., 2009). In contrast the 2-point visual control model of steering put forward by Salvucci & Gray (2004) would predict that steering will be successful as long as there are two sources of visual direction information, one in a near region for monitoring lateral position and stability and another in a far region to monitor lateral stability and future path curvature. The original conception of the near point was that it represents the center of the road and the Salvucci & Gray (2004) model attempts to keep the driver at the midpoint of the road. It would seem relatively straightforward to adapt this model to cope with the offset road positions used in our experiments, in which case we would predict similar steering behavior across all conditions as long as both near and far points are perceptually available. The near-point in the Salvucci and Gray (2004) model is the visual direction of the road center relative to the road. Either road edge could be used to provide this information, therefore we would not necessarily expect different patterns of steering if one edge is faded or removed. At the same time Salvucci and Gray (2004) state that the near point remains fixed, which might indicate that the steering system would struggle to adapt if the road edge being used is degraded/removed. Because the far point is highly flexible, it is not possible to make precise predictions about gaze fixations based on Salvucci & Gray (2004). In contrast, the active-gaze model of steering proposed by Wilkie et al. (2008) would predict that gaze will be directed toward points on the desired future path to provide prospective information. Because near-point feedback information is not used in the Wilkie et al. (2008) model, it does not make predictions about changes in steering behavior when the road edges are degraded, except when accompanied by shifts in gaze (where steering bias would be predicted to accompany gaze bias).

In the first experiment the natural patterns of gaze sampling was observed. Because changes in gaze patterns could be caused by changes in steering (rather than the other way round) our second experiment examined whether enforced eccentric fixation caused greater systematic changes to steering when road edges were degraded. Robertshaw and Wilkie (2008) showed that steering performance was worse on wider roads, with the direction of gaze causing greater steering bias. One reason for this phenomenon could have been that wider roads put the road edges further into the visual periphery and thus weakened the feedback information available to the driver. Here we test the impact of degrading road edge information directly by fading the inside and/or outside edge and enforcing fixation beyond the road edges. The present experiments use the narrow 3 m wide road from Robertshaw and Wilkie (2008), since it was shown that this road layout usually resulted in good steering performance which was largely unaffected by gaze direction. If, by fading the road edges, we observe systematic steering biases caused by gaze fixation, then this would provide strong evidence that gaze influences steering more when visual feedback information from the road edges is weak. Manipulating the quality of each road edge independently, whilst gaze direction is controlled, is also a strong test of whether both road edges provide useful information for steering. To determine the relative weighting of prospective far road information from gaze and near road feedback information from road edges we model steering using both these sources.

2 General Method

Participants

Twelve participants with normal or corrected-to-normal vision took part in both experiments. Data for three participants were removed because they were unable to maintain the three different road positions. The remaining nine participants (6 males and 3 females) had a mean age of 22.2 ± 2.8 years, ranging from 20 to 29 years old. All participants gave their informed consent, and the experiments complied with ethical guidelines approved by the University of Leeds Ethical Committee, in line with the declaration of Helsinki. The participants were naïve to the purpose of the experiments, and were instructed to steer as smoothly and accurately as they could.

Apparatus

The apparatus was similar to that used by Robertshaw and Wilkie (2008). The experiment was run on a PC (Pentium® 4 CPU 3.20GHz), using Windows XP and software specifically designed for this purpose. Direct-X graphics libraries were used. Images generated at a frame rate of 50Hz were projected, using a Sanyo Liquid Crystal Projector (PLC-XU58), onto a back projection screen with dimensions of 1.98m × 1.43m. Participants sat 1m away from this screen, so the total visual angle of display was approximately 89.4° × 71.3° filling the majority of the participants' field of view (when head and eyes were directed towards the screen center). A height-adjustable racing-style driving seat was used, and eye-height was always 1.05m from the ground (equivalent to being 61.5cm above the bottom of the screen).

Participants controlled their direction of motion using a force-feedback steering wheel (Logitech Momo Racing). The range of the steering wheel was between –32.8°/s to 32.8°/s, while rotation of the wheel increased the rate of change of heading with a minimum step size of .36°/s. Steering changes were applied to the simulated direction of motion as though rotated on a point, with no application of vehicle dynamics. The display and the steering wheel supplied data at the same rate (50Hz), so the maximum delay between movement of the steering wheel and screen position update was 20ms. The screen was situated in a matt black viewing booth, so that it was the only source of light.

The participants did not have their body or head restrained. Eye gaze data were recorded using a remote ASL (Applied Science Laboratories) 504 gaze monitoring system, which uses pan-tilt tracking to follow the participant's eye and superimposes it on the rendered scene. Gaze coordinates were recorded at 50Hz and the system can be accurate to within ±.32° when fixating a static target on a static background. In experiment 2 when steering along a simulated roadway whilst fixating a moving target, gaze fixation records were found to be accurate to within ±0.6°.

Stimuli

The stimuli consisted of a textured ground-plane with two road edges superimposed (in some of conditions only one road edge was present). Though in some ways similar to Robertshaw and Wilkie (2008), only one road width and one curvature was used, with parameters identical to the "narrow, tightly curved" roads used previously (3m wide with radius 60m). As in Wilkie et al. (2010) the starting position of the driver varied across trials: in 1/3 of trials the driver was positioned centrally between the road edges ('Central' road position), however in the other trials the driver started in an offset position, either halfway (–.75 m) towards the outside ('Outside' road position) or inside (+.75 m) of the bend ('Inside' road position) (see Fig. 1a). The steering task was to maintain the initial road position whilst steering smoothly and accurately. To vary the quality of the road edge information we used six different visibility conditions: i) both road edges visible, ii) the outside road edge faded, iii) the inside road edge faded, iv) both road edges faded, v) the outside road edge absent, or vi) the inside road edge completely absent (see Fig. 1b—conditions numbered from 1 to 6). Fadedness was achieved by reducing the luminance of the faded road edge to be 36% of the luminance of the visible road edge. Fig. 2 shows a roadway under full visibility (the fixation crosses were not used in Experiment 1). Participants had no control of speed which was set constant at 13.8 meters per second (50km/h) as in the Wilkie et al. (2010) and Robertshaw and Wilkie

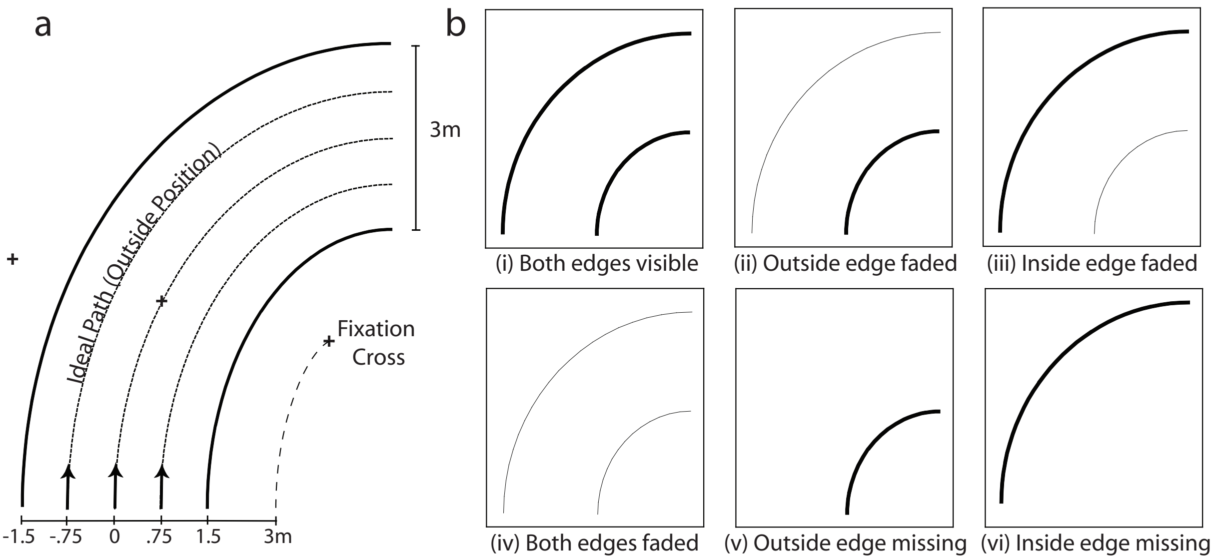

Figure 1 (a) The three different starting positions (arrows) and the three fixation crosses: fixation crosses were only used in Experiment 2. (b) The road edge visibility conditions: conditions (v) and (vi) were used only in Experiment 1.

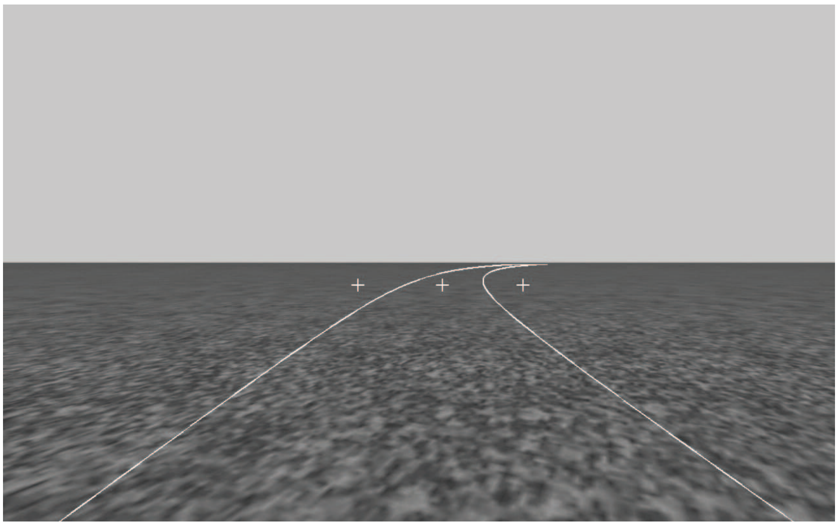

Figure 2 The experimental stimulus showing the perspective projection of the road edges on top of a naturally textured ground-plane. The fixation crosses were only used in Experiment 2 (with only one fixation cross visible per trial) and placed at a fixed position relative to the road, at the same distance as the tangent point (the apex of the inside of the bend).

(2008) studies.

Procedure

Prior to starting the experiment, participants completed 5 practice trials (each lasting the standard trial time of 7 seconds) in order to familiarize themselves with the visual environment and the device characteristics. During the practice session, we ensured that participants were able to discriminate the road edges when they were faded.

3 Experiment 1: Free Gaze

In the first experiment we wished to examine the influence of road position and road edge visibility on steering and eye-movements. In Wilkie et al. (2010) it was observed that most participants were able to keep an offset road position, but seemed to achieve this by looking towards the position in the road they wanted to steer through. Here we examined whether varying the visibility of the road edges alters the ability of participants to gauge their position on the road, and whether gaze patterns change when the quality of the visual information was degraded. We also determined whether a single road edge can provide sufficient error feedback and prospective information and whether the inside road edge is predominant (as would be expected from the tangent point theory).

Method

Participants were simply instructed to steer smoothly along each roadway trying at all times to maintain their starting position on the road (as in Wilkie et al., 2010). Two blocks consisting of 54 trials (3 road positions × 6 road edge visibility conditions × 6 repetitions each, of which three repetitions were right bends, and three were left) were presented randomly. The six road edge visibility conditions and the three road positions along with the ideal path for each are depicted in Fig. 1. Although participants were aware that their eye-movements were being recorded, no mention of the importance of gaze was made in order to record eye-movements that were as natural as possible. The direction of gaze was determined by recording the point of gaze on the projection screen and extrapolating into the perspective-correct rendered scene. Gaze bias was measured by calculating the deviation of gaze from the center of the road for each frame of each trial. Additionally, the position of the participant on the road was recorded and the deviation from the ideal path was calculated for each frame of each trial providing measures of steering precision (root mean square deviation: RMS) and steering bias.

Steering bias is a measure of whether participants spent most of the trial either oversteering (denoted by positive values in bias) or understeering (denoted by negative values in bias), whereas RMS error is a useful measure of overall deviation from the ideal path, irrespective of over/understeer. The first 9.2 m of each road were straight followed by a stepped change in curvature and so the data from the initial 4 s of each trial were ignored, with steering analyses conducted on the final 3 s of each constant curvature bend.

In both experiments repeated-measures ANOVAs were used to analyze all the data, unless otherwise stated. Sphericity was taken into account, and adjusted degrees of freedom and p values are reported using the Greenhouse-Geisser correction when appropriate.

Results

Steering Analysis

Steering Bias In this experiment participants were placed at one of three initial positions with respect to the center of the road and asked to maintain their distance from the road edges. The required steering bias to maintain the 'Central' road position would be 0 m, for the 'Outside' position it would be -0.75 m and for the 'Inside' position it would be 0.75 m. To perform the task at each position participants needed to steer slightly different curvatures: 'Central' road position (radius = 60 m), 'Inside' road position (radius = 59.25 m), and the 'Outside' road position (radius = 60.75 m). The results of the 3×6 repeated-measures ANOVA (3 road positions by 6 visibility conditions—see Fig. 1) used to analyze the data are summarized in Table 1. There was a significant main effect of road position in steering bias, but no significant effect of visibility nor an interaction between road position and visibility. Because steering bias was unaffected by road edge visibility, Fig. 3 only shows the main effect of road position. Participants generally maintained a position on the road close to that required by the instructions, albeit not perfectly, and a drift towards the road center was observed (oversteer in the outside road position relative to the required position and understeer in the inside road position relative to the required position). Repeated contrasts showed that the 'Outside' starting position caused significant oversteer compared to when starting in the 'Central' position of the road ($F(1,8) = 23.96, p = .001, \eta_p^2 = .75$), whereas the 'Inside' starting position caused significant understeer compared to starting at the 'Central' road position ($F(1,8) = 10.38, p = .012, \eta_p^2 = .56$). It seems therefore that, while participants were unable to precisely maintain an offset position in lane, they were able to adjust their steering sufficiently to stay on the correct side of the road.

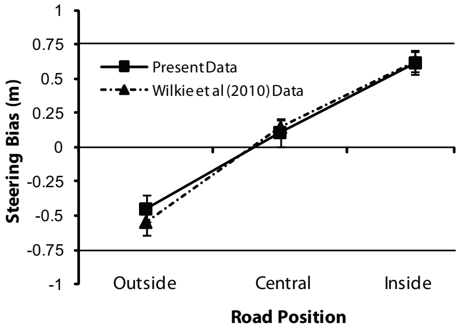

Figure 3 Effect of initial road position on steering bias. Steering bias relative to the center of the road with data from Experiment 1 (squares) as well as data from Wilkie et al. (2010) in triangles, shown here for comparison. The required bias for each of the road positions is depicted by the three horizontal lines. Bars = *SEM*.

In addition to the effects caused by road position, there does seem to be a general tendency to oversteer. This oversteer is consistent with previous research examining steering around bends with the same width and curvature (Robertshaw & Wilkie, 2008) and it has also been shown that on curved roadways the Fajen and Warren (2003) steering model results in oversteer (Hamner, Singh, & Scherer, 2006).

Steering Error (RMS) The 3×6 repeated-measures ANOVA (3 road positions by 6 visibility conditions—see Fig. 1) in the steering error (RMS) measure is summarized in Table 1. Although there was no significant effect of road position, there was a significant effect of road edge visibility, and most importantly, a significant interaction between road position and road edge visibility in steering error. Fig. 4 shows how steering was differentially affected at each road position when road edge visibility changed. The tangent point hypothesis would predict large errors when the inside road edge was removed ('No Inside') and there to be little effect of removing the outside road edge ('No Outside'). It might also predict that fading the inside should be have a larger effect than fading the outside, and fading both inside and outside should be identical to fading just the inside. This is not the pattern of errors that we observe. In fact there was no significant effect of road edge visibility when examining just the 'Central' road position (Fig. 4, gray bars; $F(5,40) = 1.43, p = .23$). This suggests that participants could still steer just as well when the inside edge was either faded or even removed as when it was fully visible. Steering errors were affected by road edge visibility at non-central positions. Fading the road edges had a weak effect on steering errors which makes it is hard to see a consistent pattern but there is evidence that both inside and outside road edges are being used in these conditions. Steering was more impaired when both road edges were faded than when just the inside road edge was faded when trying to maintain a road position near the inside road edge ($F(1,8) = 12.36, p = .008, \eta_p^2 = .61$). This effect can be more clearly seen when outside or inside road edges were removed (Fig. 4, 'No Outside' and 'No Inside' conditions). Essentially steering errors increased when the nearest road edge was removed, with an interaction when comparing the 'Inside' and 'Outside' road positions for 'No Outside' and 'No Inside' road edge visibility conditions ($F(1,8) = 17.01, p = .003, \eta_p^2 = .68$).

When maintaining a central road position it seems that either road edge could guide steering, but when trying to maintain a road position next to a faded/missing road edge then sampling information from the other edge is more of a challenge. An obvious way participants could maintain their road position when the edge nearest them was faded would be by shifting gaze towards the visible road edge. In the next section we examine gaze behaviors to see whether there were systematic shifts linked with road position and road edge visibility.

Gaze Analysis

So far, we have only considered the influence of the visual conditions upon steering performance. To determine whether gaze behavior was also affected, we calculated gaze bias and analyzed it using a 3 (road positions) × 6 (visibility conditions) repeated-measures ANOVA. There were main effects for road position ($F(1.19, 9.49) = 77.41, p < .001, \eta_p^2 = .91$),

Table 1 *ANOVA results from Experiment 1*

	Steering Bias				RMS Error			
	F	df (error)	p	η_p^2	F	df (error)	p	η_p^2
Road Position	19.33	1.25 (10.04)	.001*	.71	1.06	2 (16)	.37	.
Edge Visibility	1.15	2.12 (17.00)	.34	.	8.33	5 (40)	<.001**	.51
Position × Visibility	.74	10 (80)	.69	.	4.27	10 (80)	<.001**	.35

* Significant at the $p < .05$ level,
** Significant at the $p < .001$ level

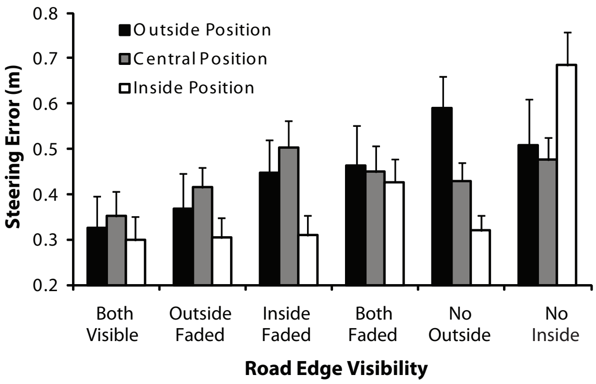

Figure 4 Steering error (RMS) for each road position and each road edge visibility condition. The grey bars represent the central road position, the black bars the outside road position and the white bars the inside road position. Bars = *SEM*.

and road edge visibility ($F(1.71, 13.73) = 18.55, p < .001, \eta_p^2 = .70$) as well as a significant interaction between road position and road edge visibility ($F(10, 80) = 6.65, p < .001, \eta_p^2 = .45$).

Fig. 5a shows that gaze shifted in the direction of the required road position, so we will consider in more detail the main effect of road position. Repeated-contrasts revealed that gaze bias was significantly different for the 'Inside' road position (mean = 0.75 m, *SEM* = .08) than the 'Central' road position (mean = .04 m, *SEM* = .08) ($F(1, 8) = 49.81, p < .001, \eta_p^2 = .86$), and also gaze for the 'Central' road position was significantly different than for the 'Outside' position (mean = -0.56 m, *SEM* = .11) ($F(1, 8) = 97.63, p < .001, \eta_p^2 = .92$). The general pattern demonstrated here confirms previous findings examining shifts of gaze bias in relation to a required road position (Wilkie et al., 2010) where participants look in the direction they want to go and/or steered in the direction they were looking.

The interaction between road position and road edge visibility on gaze bias is mostly driven by the 'Inside Missing' and 'Outside Missing' visibility conditions (Fig. 5a), with the 'Faded' visibility conditions resulting in gaze biases similar to when both edges were visible[2]. As such, to analyze this interaction, comparisons between all the three road positions and only three of the visibility conditions (shown in Fig. 5a by the solid black lines with circles: 'Inside Missing', 'Outside Missing' and 'Both Visible') was carried out[3]. Comparing the 'Inside Missing' and 'Both Visible' conditions and the 'Inside' and 'Central' road positions a significant interaction was found ($F(1, 8) = 6.70, p = .03, \eta_p^2 = .46$), suggesting that the difference between these two visibility conditions in the 'Central' road position was smaller than the difference in the 'Inside' road position (see Fig. 5a). It seems, therefore, that participants appeared to shift their gaze towards the center of the road (and presumably towards the visible outside road edge) when they were positioned nearer the invisible inside road edge. When the same two visibility conditions ('Inside Missing' and 'Both Visible') were compared in the 'Central' and 'Outside' road positions, another significant interaction was found ($F(1, 8) = 33.82, p < .001, \eta_p^2 = .81$), suggesting that gaze was influenced by removing the inside road edge when maintaining the 'Central' road position but not in the 'Outside' road position (see Fig. 5a). We see equivalent patterns of results when comparing the 'Outside Missing' and 'Both Visible' conditions in the 'Inside' and 'Central' road positions: there is no difference in gaze for the 'Inside' road position, but a significant

[2]An ANOVA on the visibility conditions excluding the 'Inside Missing' and 'Outside Missing' conditions resulted in no significant differences between visibility ($F(1.01, 8.73) = 2.60, p = .14$), nor any interaction ($F(6, 48) = 1.52, p = .19$).

[3]The 'Both Visible' condition was chosen not only for being a suitable control, but also for being representative of the faded visibility conditions that were not examined further.

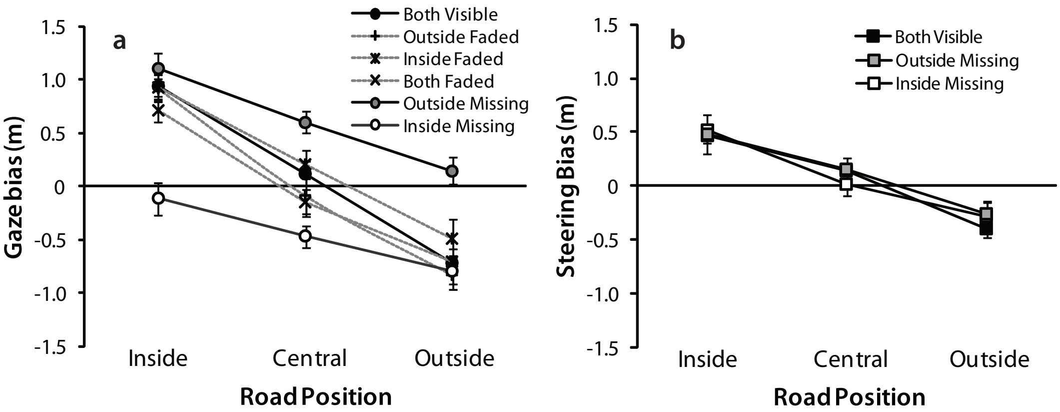

Figure 5 (a) Gaze bias relative to the center of the road for all road edge visibility conditions, and (b) steering bias relative to the center of the road for the three road visibility conditions that had differential effects upon gaze (the other road edge visibility conditions overlapped those presented here). Bars = *SEM*.

difference does occur when in the 'Central' road position ($F(1,8) = 8.95, p = .017, \eta_p^2 = .53$), with participants looking more towards the visible inside road edge rather than the center of the road (Fig. 5a). The interaction between the 'Inside Missing' and 'Both Visible' conditions in the 'Central' and 'Outside' road positions approached significance ($F(1,8) = 5.08, p = .054$).

The gaze analyses so far provide a useful indication of the general direction of gaze, but calculating gaze bias in this way makes it difficult to determine the underlying dynamic gaze patterns. In order to determine the distribution of gaze fixations across the road we binned gaze data into 5 zones (each bin .75 m wide; see Fig. 6). Two zones fell ± .375 m around each of the road edges, and the other three were ± .375m around each of the three required paths (refer to Fig. 1a). Fig. 6 shows the proportion of gaze fixations falling in each zone for three road positions and three road edge visibility conditions.

It can be seen in Fig. 6 that the largest proportion of gaze fixations fell either around the desired path or the road edge nearest the path (when it was visible). When steering in the center of the road with both road edges visible then participants looked on or around their trajectory and spent less than 20% of their time looking at either road edge. This pattern drastically changes when either the inside or outside road edge was removed: gaze shifted to sample information from either the roadway near to the visible road edge or on to the edge itself. This pattern of fixations suggests that participants were capable of sampling the position of the road edges peripherally under normal visibility conditions, but the absence of a road edge resulted in gaze shifting in the direction of the remaining visible edge. This means that there are very few fixations near the inside road edge when the required lane position was near the outside edge or the center of the road, except when the outside road edge was removed (white zone in Left Panel of Fig. 6). When participants tried to maintain the inside road position when the inside road edge was visible a high proportion of gaze falls around that edge. Although it might seem that this provides support for the tangent point theory, when participants attempted to maintain other road positions there were far fewer inside road edge fixations. The global pattern of gaze fixations across all conditions then is not consistent with extensive tangent point fixation.

Discussion

In Experiment 1 participants were asked to maintain one of three possible road positions (Fig. 1a) under six different visibility conditions (Fig. 1b). Participants generally drifted towards the center of the road (as observed in Wilkie et al., 2010) and had a tendency to oversteer (consistent with Coutton-Jean, Mestre, Goulon, & Bootsma, 2009; Gawron & Ranney, 1990; Hamner et al., 2006; Robertshaw & Wilkie, 2008). When attempting to steer in the center of the road, there was no increase in steering error when either the inside or outside road edge was faded or removed. This does not support the tangent point model of steering, but is consistent with using an arbitrary near and far point as per the proposals of Salvucci & Gray (2004). Interestingly, steering error (RMS) increased significantly when participants tried to maintain their position near a

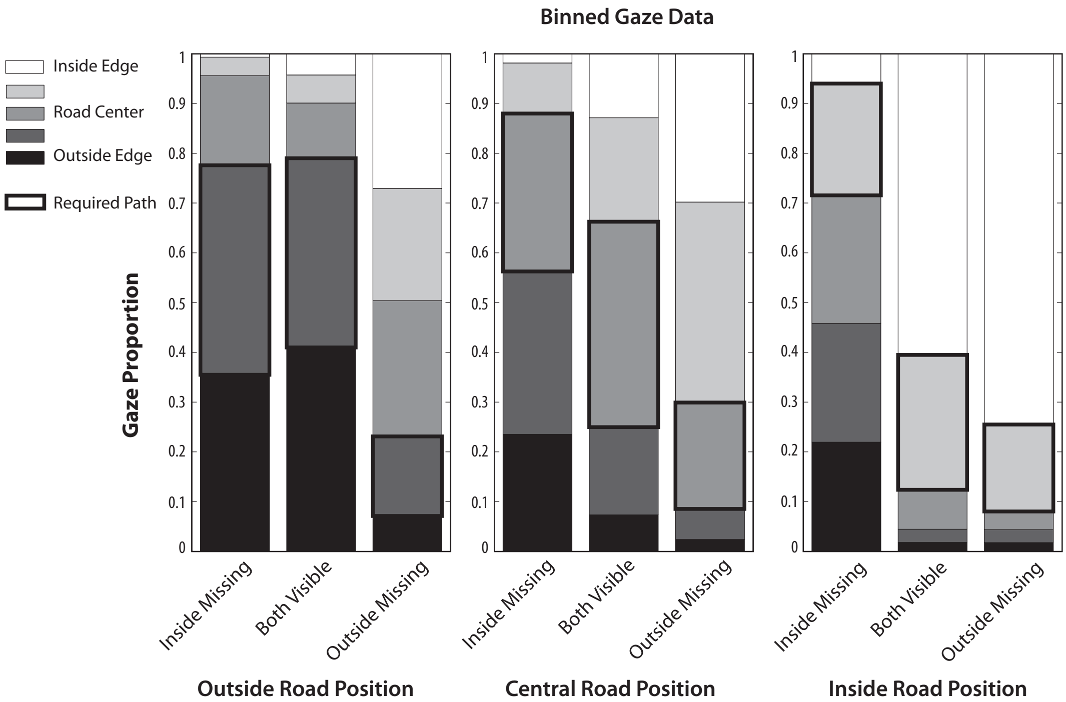

Figure 6 The proportion of gaze fixations falling in each roadway zone for three different road positions and three road edge visibility conditions. Black indicates a zone around the outside road edge, and white a zone around the outside edge. The bold black border indicates the zone that includes the road position the participants were attempting to maintain.

road edge that was missing. This finding suggests that participants naturally rely upon information from the road edge nearest them, again demonstrating that participants did not rely solely on the inside road edge[4]. Consistent with the proposals of Wilkie and Wann (2003, 2003) participants tended to look at points along the trajectory they were trying to maintain, however, when the nearest road edge was missing, their gaze shifted in the direction of the remaining visible road edge. Under these conditions, gaze bias no longer matched steering bias (compare Figs. 5a and 5b, especially the 'Outside Missing' visibility condition in the 'Outside' road position, and the 'Inside Missing' visibility condition in the 'Inside' road position). It seems that these conditions created a situation with competing demands on active gaze sampling: they were attempting to obtain high quality position-in-road information from the road edges, whilst also using the direction of gaze to aid the prospective control of steering. This change in gaze behavior is not without a cost, since it is associated with an increase in steering errors (RMS) as can be seen in Fig. 4c. We suggest that this provides evidence that although gaze and steering bias can be decoupled, this leads to less accurate steering than when gaze and steering trajectory are kept more tightly coordinated.

4 Experiment 2: Fixed Gaze

In Experiment 1 we found that road position and road edge visibility had an influence over both steering and gaze behaviors. The data shows there is usually a tight coupling between where the participants are trying to steer, the trajectories that they take, and where in the scene they are looking. The difficulty with interpreting these results is that it is hard to be sure whether the gaze behavior

[4]This can be seen most clearly for the 'Outside Missing' and 'Inside Missing' road-edge visibility conditions in Fig. 4: the absence of the outside road-edge was detrimental for participants trying to stay in the 'Outside' road-position (near the outside road-edge), whereas for those maintaining the 'Central' or 'Inside' positions there was no effect of removing the outside road-edge. Similarly, when the inside road-edge was removed, participants trying to maintain the 'Inside' position had elevated errors, whereas there was little effect of removing this information for those maintaining the 'Central' or 'Outside' road positions.

leads steering, or whether steering behavior causes the changes in gaze patterns. It is also difficult to determine the extent to which each road edge is influencing steering, since small shifts in gaze patterns could in some way compensate for degraded peripheral information. In the next experiment we ran similar trials to Experiment 1, but controlled participants' gaze by asking them to look at fixation crosses placed at specific points in the scene (kept constant relative to the road). We then observed the effect that gaze location had upon steering, as well as any interactions between gaze location, road position, and road edge quality. We used the faded road edge conditions (rather than road edge missing conditions) because we wanted a quantifiable amount of information to be available from both road edges. Whilst the effect of the faded road edges on steering error were not large in Experiment 1, dynamic gaze patterns may have been used to compensate for degraded information. The second experiment examines this explanation by restricting gaze. The primary focus, however, is to determine whether gaze has a greater influence over steering when road edges are degraded. Fading the road edges is akin to the types of degradation associated with low-light or peripheral viewing and so should inform us whether we might expect to see these sorts of biases in real world conditions.

Method

Participants were again asked to steer around a series of bends of constant curvature, trying to maintain their starting distance from the road edges (with three possible road positions: road center, or towards the inside or outside of the bend) but this time they were instructed to direct their gaze at a fixation cross placed in the scene. While superficially similar to Readinger et al. (2002) our method has a number of important differences. Readinger et al. (2002) did not use eye-tracking so participants had to monitor the orientation of a Landolt-C Fig. at the point of fixation and respond each time it changed orientation. This meant that participants were actively carrying out a secondary task that required attention to be directed at the point of fixation, which may have reduced the degree to which peripheral information was monitored (Williams, 1982) and so magnified the effect of eccentric gaze. Readinger et al. (2002) used fixations that were held at a constant angle (up to ±45°) whereby changes in vehicle position and orientation left gaze angle unaffected (akin to looking at a mark on the vehicle windscreen). Such fixations are, however, less usual in real locomotor settings since fixations outside of the car tend to fall on the ground or on vehicles on the road ahead, and eccentric targets are usually tracked during their approach. We are interested in the fixations in the world that are used to control steering. The tangent point is an optical feature on a bending road that that will move laterally when drifting within a lane. Any steering bias towards the point of fixation reduces the degree of eccentricity and therefore also reduces the gaze offset. To mimic the properties of the tangent point we presented our fixation points the same distance ahead, but laterally offset (these conditions match a subset of those used previously by Robertshaw & Wilkie, 2008). Road width has also been shown to have an influence over steering bias with gaze having greater influence on wider roads (Robertshaw & Wilkie, 2008). Readinger et al. (2002) used a very wide (7.5m) road, but we use the standard 3m UK road width to see if fading the road edges increases the impact of eccentric gaze fixation. Because of the differences in fixation task, gaze eccentricity and road width the biases observed in our fixation experiment may be expected to be smaller than the .25–.4m found by Readinger et al. (2002).

The fixation conditions we used were similar to those used in Robertshaw and Wilkie (2008) except we used only three possible fixation locations. A fixation cross was placed in the distance (at the same distance as the tangent point) either at the center of the road, or 3 m away from the center of the road (1.5m beyond either the outside or inside of the bend; see Fig. 1a and Fig. 2). As in Experiment 1, the visibility of the road edges was manipulated, but only four visibility conditions were used: 'Both Visible', 'Outside Faded', 'Inside Faded', and 'Both Faded'.

The participants were presented with three blocks of 72 trials each (4 road-visibility conditions, 3 road position conditions and 3 fixation conditions, with 6 trials repeated for each condition, 3 of these trials were left bends and 3 were right bends which were collapsed across in the analysis). The same measures were used as in Experiment 1, and as previously data from the straight section of the road were ignored with analyses performed only on the final 3s of constant road curvature.

Results

Two repeated-measures ANOVAs were performed, one for steering bias and one for steering error

(RMS) with the following levels: 3 (fixation points) × 3 (road positions) × 4 (visibility conditions). The results of the ANOVAs are shown on Table 2. As in Experiment 1, sphericity was taken into account, and adjusted degrees of freedom and *p* values are reported using the Greenhouse-Geisser correction when appropriate.

The effect of road edge quality and road position when fixating

Steering Bias In Experiment 1 we did not observe changes in steering bias or steering error for the faded road edge conditions (it was only when road edges were removed that we saw an interaction with road position). One explanation for this is that active gaze fixations were being used to compensate for degraded visual information. In Experiment 2 gaze was fixed and so we might expect to see a greater effect of faded road edges. Fig. 7 shows the interaction between road edge quality and road position for steering bias (Table 2). Participants were best able to adjust their steering towards the required position when both edges were visible. When road edges were faded participants also adjusted their position in the correct direction but there was a tendency to underestimate the degree of offset that was needed (the steering bias gradients are generally flatter). There was a general shift in bias for different road fadedness positions with participants tending to oversteer when the inside road edge was faded and understeer when the outside road edge (or both road edges) were faded. It seems, therefore, that fading road edges has an effect on steering when gaze is fixed.

Steering error There was an interaction between road edge quality and road position for steering error as well as a triple interaction (Table 2). Fig. 8 shows the pattern of steering errors for all conditions. In general participants were best when fixating near the road position they were maintaining and worst when looking far from this position. This leads to a differential effect of fadedness and position depending upon the direction of fixation. Overall the largest errors were exhibited when steering in the outside position, but only for central and inside fixations. Steering errors also increased in the outside fixation but only for the inside position when both road edges were faded.

Experiment 2 was principally designed to test the effect of eccentric gaze fixations when road position and road edge visibility were manipulated.

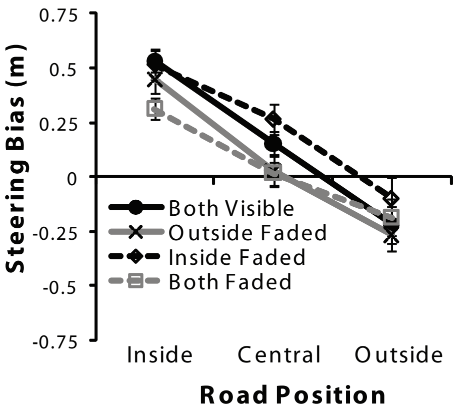

Figure 7 The interaction between road position and road edge visibility on steering bias in Experiment 2 (averaged across the three fixation conditions). The steering task required participants to steer at 0.75m to maintain the inside road position and at −0.75m to maintain the outside position. When the inside edge was faded participants oversteered in the outside position, and when both edges were faded participants understeered in the inside position. Bars = SEM.

The next sections consider in more detail whether there were systematic changes in steering bias and steering error for eccentric gaze fixations.

The effect of fixation on steering bias

The ANOVA for steering bias showed that there was no interaction between fixation and road position conditions, or between fixation, road position, and visibility conditions (Table 2). The fixation conditions did influence steering, with fixations 'Far Outside' producing significantly different steering bias than fixations in the middle of the road ($F(1,8) = 30.80, p < .001, \eta_p^2 = .79$), but no differences were found between fixations on the 'Center' and 'Far Inside' points ($F(1,8) < 1$). Fig. 9a shows that fixating beyond the outside of the bend caused participants to understeer whereas fixating on the inside and the center of the bend resulted in oversteer. This finding is broadly in line with the predictions of the Wilkie and Wann 'Active Gaze' model, which suggests that participants would steer in the direction of gaze. Although fixating the road center did result in oversteer, this seems to be a natural part of steering (as observed in Experiment 1 and by Robertshaw and Wilkie, 2008 and Wilkie et al., 2010).

Because there was a significant interaction between the fixation conditions and road edge visibil-

Table 2 *ANOVA results from Experiment 2*

	Steering Bias				RMS Error			
	F	df (error)	p	η_p^2	F	df (error)	p	η_p^2
Road Position (P)	63.76	2 (16)	<.001**	.89	9.24	2 (16)	.002*	.54
Edge Visibility (V)	7.18	3 (24)	.001*	.89	10.41	1.73 (13.84)	<.001**	.56
Fixation (F)	19.26	2 (16)	<.001**	.68	.61	2 (16)	.57	.
P × V	3.71	6 (48)	.004*	.32	4.11	6 (48)	.002*	.34
F × V	8.86	1.97 (15.72)	.003*	.52	1.24	6 (48)	.30	.
F × P	.55	4 (32)	.70	.	17.94	4 (32)	<.001**	.69
P × V × F	.67	12 (96)	.78	.	2.84	12 (96)	.002*	.26

* Significant at the $p < .05$ level,
** Significant at the $p < .001$ level

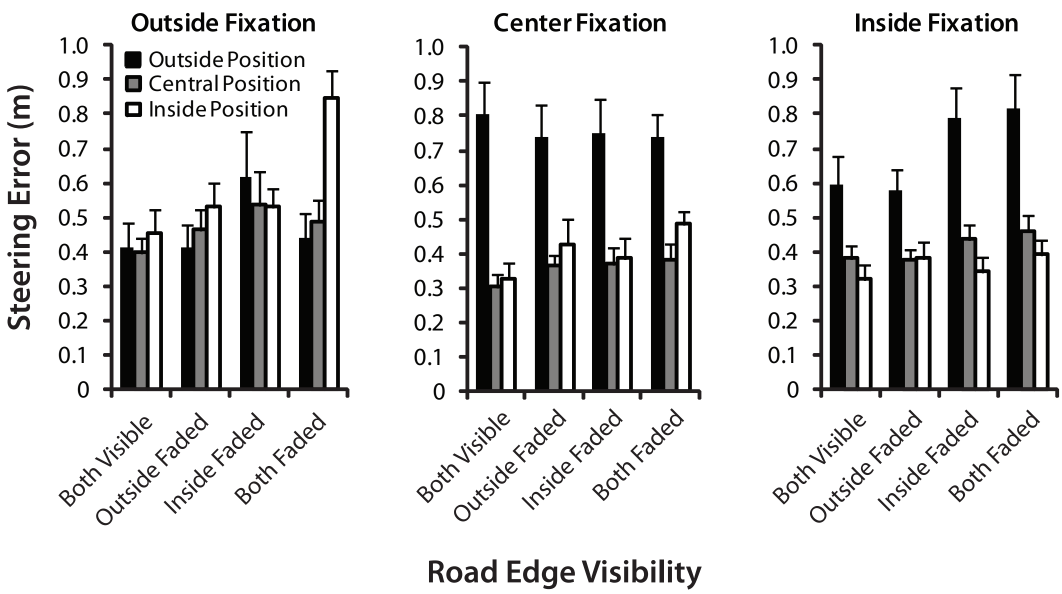

Figure 8 The interactions between road position and road edge visibility for different fixations on steering errors (Experiment 2). Bars = *SEM*

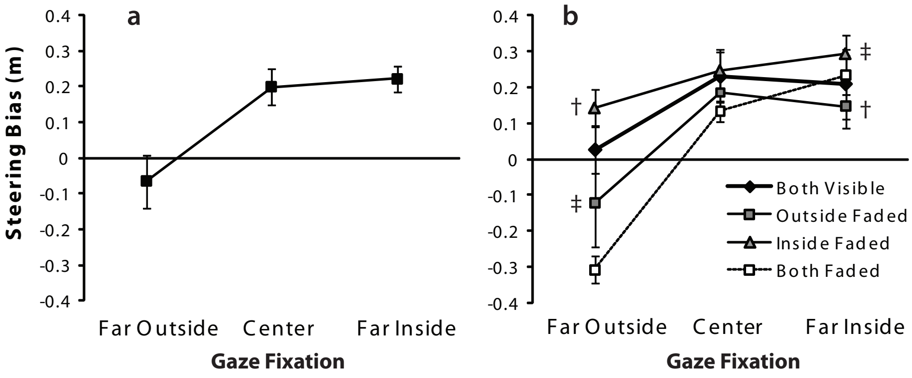

Figure 9 (a) The main effect of fixation on steering bias, and (b) the interaction between fixation and road edge visibility (averaged across road positions). Fixating 'Far Outside' was a point −1.5m beyond the outside road edge (and 3m from the road-center), whereas 'Far Inside' was a point 1.5m beyond the inside road edge (3m from the road-center)—no fixations were on road edges. The symbols indicate the conditions where we would predict the smallest (†) and greatest (‡) influence of gaze when a single road edge is faded. Bars = *SEM*

ity, we should expect differential effects of fixation based upon the quality of visual road edge information (see Fig. 9b). It can be seen that there is little effect of eccentric gaze fixation when both road edges are visible, and this is consistent with the findings of Robertshaw and Wilkie (2008) also using narrow (3m) roads. To understand the interaction better, we first compared the effects of the inside and outside fixation points in the 'Both Visible' and 'Both Faded' conditions. There was a significant interaction ($F(1,8) = 12.56, p = .008, \eta_p^2 = .61$) whereby there was greater understeer when fixating outside of the road when road edges were faded than when road edges were visible, whereas oversteer was similar when fixating inside of the road for both visibility conditions (see Fig. 9b, filled diamonds and open squares).

We examined whether the faded road edge conditions ('Inside Faded' and 'Outside Faded') were differentially influenced by fixation direction ('Far Inside' or 'Far Outside' of the bend) but no significant interaction was found ($F(1,8) = 3.63, p = .09$). While this indicates that the systematic change in steering bias was similar for these conditions it could be predicted that fixating a point near a faded road edge (shown with ‡ in Fig. 9b) should have a greater influence over steering than when fixating near a strongly visible road edge (shown with † in Fig. 9b). In order to examine this hypothesis, two paired-samples t-tests were performed: one between the 'Inside Faded' in the 'Far Outside' fixation condition (mean = .142 m, *SEM* = .098) and 'Outside Faded' between the 'Far Inside' fixation condition (mean = .147 m, *SEM* = .037), both conditions where the fixation point was near a strongly visible edge (shown with † in Fig. 9b), and one between the 'Outside Faded' in the 'Far Outside' fixation condition (mean = -.123 m, *SEM* = .069) and 'Inside Faded' in the 'Far Inside' fixation condition (mean = .293 m, *SEM* = .029), both conditions where fixations where near a faded road edge (shown with ‡ in Fig. 9b). This confirmed that steering bias was not significantly different for the conditions where fixations were near a strongly visible road edge ($t(8) = -.062, p = .95$), but there was a significant difference between the conditions when the fixations fell near a faded edge ($t(8) = -7.180, p < .001, r = .93$), with participants being more influenced by their gaze fixations (and thus steering in that direction) when there was weaker information from the road edge.

The effect of fixation on steering error

Contrary to steering bias, there was no main effect of fixation on RMS steering error, or a significant interaction between fixation and road edge visibility, but a significant interaction was found between fixation and road position (see Fig. 10).

To interpret this interaction we compared fixations on the outside versus fixations in the center, which interacted significantly with inside and outside road positions ($F(1,8) = 14.63, p = .005, \eta_p^2 = .65$) and also outside and central positions ($F(1,8) = 7.54, p = .025, \eta_p^2 = .48$). It seems that steering errors increase when looking away from the desired road position: when looking at the 'far inside' fixation steering was best in the inside position and worst

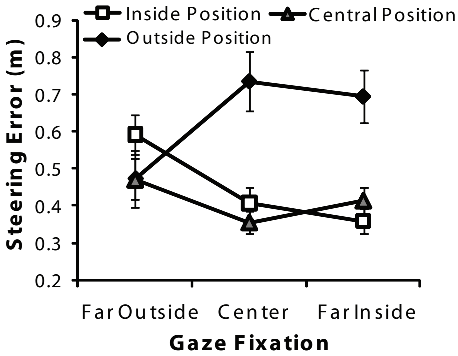

Figure 10 The interaction between fixation and road position. Bars = *SEM*.

in the outside position (and vice versa). This effect is not symmetrical, however, since steering near the outside of the road was more difficult when fixating the road center than steering near the inside of the road. This effect was not found in Experiment 1 with all three road positions producing similar steering errors. Since the same participants were used for both of these experiments, the only differences were the gaze restrictions imposed in Experiment 2. The outside position may have been more difficult to maintain since it would have required a greater degree of understeer than normal, but the free eye-movements in Experiment 1 seemed to allow participants to compensate. This interpretation is further supported by the overall elevated steering errors observed in Experiment 2 (see General Discussion). None of the conditions in Experiment 2 allowed fixation of the tangent point so if steering was dependent upon fixating this feature then we should have observed large errors in all cases. It could be argued, however, that fixating on the 'Center' or 'Far Inside' point puts gaze closer to the tangent point. Steering errors were actually greater for these conditions when participants were in the outside position, making it difficult to argue for a tangent point and gaze proximity advantage (Fig. 10).

Modeling the relative influence of gaze and road edges in steering bias

So far we have independently examined the effect of road edge visibility and gaze offset on steering. In order to determine the relative contribution of feedback from road edges and prospective information from gaze we can examine the steering biases (as shown in Fig. 9b) when both road edges were visible or faded, and determine the change in bias between fixating 'Far Outside' and 'Far Inside' (Fig. 11). By modeling steering using Equation 4 from Wilkie et al. (2008) we can determine the relative weighting of each information source.

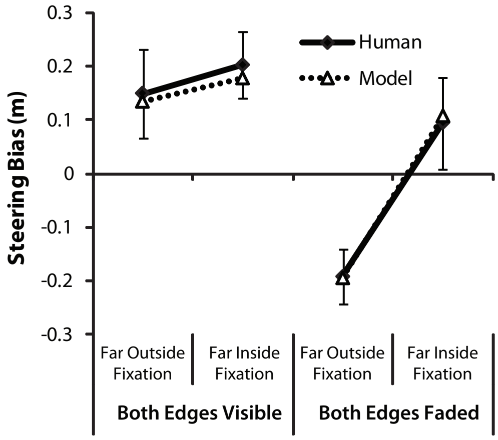

Figure 11 The steering bias caused by gaze offset during two road edge visibility conditions, for human data (solid line, filled diamonds) and modeled trajectories (dotted line, open triangles). For both humans and the model, fixation was 'far outside' or 'far inside' of the road when both road edges were either visible or faded (as described in the methods). The modeled data was fitted using iterative adjustment of the steering model of Wilkie et al. (2008) keeping the following parameters constant: a damping value (b) of 0.4, response speed k_1 = 4.7 and k_2 = 1.0. The error bars on the human data represent the standard error of the mean.

If gaze had no influence on the steering trajectories we would expect to see no change in steering bias. If road edge visibility did not influence steering trajectories we would expect to see a similar change in steering bias whether the edges were visible or faded (with the direction of gaze being the sole determinant of steering bias). Fig. 11 clearly shows that both sources of information influence steering. In the 'Both Visible' road edge condition there is a negligible effect of gaze on steering bias (a difference of 0.05m) indicating that gaze is largely suppressed by the presence of the visible road edges (as expected from previous work). When the luminosity of the road edges is reduced to 1/3 of its original value ('Both Faded' condition) the change in steering bias increases six-fold (0.29m). The data presented here (e.g. Fig. 9) could be used to suggest that the road edges provide a variable signal that can be degraded rather than being either present or absent (in the same way that retinal flow can be degraded; Wilkie & Wann, 2002). In order to quantify the relative contribution of gaze and road edge visibility in steering we adapted the Wilkie et al. (2008) model, in order to include the visual information one might get from the road edges and then varied the weightings of gaze and road edges in order to generate steering trajectories. The point-attractor model proposed by Wilkie et al. (2008) calculates the acceleration of steering response ($\ddot{\theta}$) that closes down an angle (α) and change in angle ($\dot{\alpha}$) at a smooth rate (dictated by the response-rate (k_1 and k_2) and damping (b)):

$$\ddot{\theta} = k_1\dot{\alpha} + k_2\alpha - b\dot{\theta} \tag{1}$$

The $\dot{\alpha}$ term was originally calculated using three perceptual estimates: the extra-retinal estimate of the rate of change in target direction (${}_eE\dot{R}D$), retinal change in target direction (${}_eV\dot{D}$) and the estimate of the rotation within the flow field (${}_eRF$). Since there was no manipulation of retinal flow in these experiments ${}_eRF$ was not included in the present modeling. The ${}_eV\dot{D}$ estimate in this case was supplied by the movement of the road edges on the retina, which meant that the model would be gradually pushed towards a state where the road edges did not move (which would occur when steering a constant curvature trajectory that matches the road curvature). In the original model, α was mainly supplied by an extra-retinal estimate of the target direction (${}_eERD$) that is available when fixating a target, but it was also suggested that a retinal estimate of the visual direction of a target (${}_eVD$) could be used in cases where a visible reference for the locomotor vehicle was available, e.g. the bodywork of a car (Wilkie & Wann, 2002). Here we use ${}_eVD$ to represent the near-road perceptual information available from the two road edges. Both road edges needed to be used so that closing down the angle to one edge, increased the angle to the other, and therefore this term pushed the model towards maintaining a central position[5].

Substituting $\dot{\alpha}$ and α in Equation 1 with their perceptual estimates we get:

$$\ddot{\theta} = k_1(\beta_1\, {}_eE\dot{R}D + \beta_2\, {}_eV\dot{D}) + k_2(\beta_3\, {}_eERD + \beta_4\, {}_eVD) - b\dot{\theta} \tag{2}$$

The β weights when combined always equaled 1 ($\beta_1 + \beta_2 = 1$; $\beta_3 + \beta_4 = 1$). The modeled data from Fig. 9 when both road edges were visible were generated using $\beta_2 = \beta_4 = .95$ (thus gaze only contributed 5%). Although the weighting of the road edges might seem high, this merely reflects the degree of suppressed steering bias observed in our data. For comparison Wilkie and Wann (2002) supplied a retinal direction signal from the visible bodywork of the vehicle which was weighted as high as 75% in the presence of active gaze signals. In order to model the "Both Faded" conditions the weighting of the road edge signals needed to be decreased to $\beta_2 = .75$ and $\beta_4 = .4$. These weightings show that both α and $\dot{\alpha}$ estimates rely more upon extra-retinal direction information when the road edges were degraded, but this shift is greatest for α. This asymmetry in weighting may provide another explanation of the asymmetric biases observed in Fig. 9b and Fig. 11. Our participants exhibited large degrees of understeer when fixating outside of the road edge, but no equivalent shift towards oversteer when fixating inside of the road edge. It seems, therefore, that fixations 'far inside' provide a set of perceptual estimates that provide a more consistent steering output, when compared to fixations 'far outside'. When implemented within a robotic platform this model can be prone to understeer (Wilkie, Wann, & Allison, 2011), and under some of the present conditions we find this captures human performance quite well.

Discussion

As expected, there was little effect of gaze fixation when both road edges were visible, which is consistent with the previous findings of Robertshaw and Wilkie (2008)[6]. When both road edges were faded (Fig. 9b, dotted lines) participants steered more towards the eccentric fixation points than when both edges were visible. This supports the assertion of Robertshaw and Wilkie (2008) that gaze fixation will have a larger effect on steering when visual feedback information about position in lane is weaker. This was previously observed on roads of different widths, with gaze direction seeming to influence steering more when traveling on wider roads. The argument put forward by Robertshaw and Wilkie (2008) was that when the road edges were further apart they were placed away from central vision and so the visual information could be

[5] Whilst it would, in principle, be possible to adjust the model to maintain different offset starting positions, this was beyond the scope of the current MS. We therefore present data simply for the central road-position.

[6] Robertshaw & Wilkie (2008) used a variety of road widths and curvatures, and only found effect of direction of fixation on 6m wide roads. Here we used 3m wide roads with bends of 60m radius where little influence of gaze was found previously.

considered weaker. Here we directly manipulated the strength of visual information and have shown that road edge luminance does indeed alter the impact of gaze direction upon steering. There are two road edge visibility conditions which can be examined to test this theory further (symbols in Fig. 9b): when only one road edge was faded ('Outside Faded' or 'Inside Faded') we would expect to see larger steering biases when fixating near the faded edge (‡) compared to fixating near the visible edge (†). We would predict that there should be larger oversteer when fixating inside of the road when only the inside road edge is faded, compared to when only the outside road edge is faded. Similarly, there should be more understeer when fixating outside of the road edge when only the outside road edge is faded, compared to when only the inside road edge is faded. This is exactly the pattern of results that can be seen in Fig. 9b. This reinforces the suggestion that poor visual information from the faded edge combined with poor visual information from the peripheral view of the visible edge to reduce the immediate error feedback available from these road edges and ultimately increases the influence of gaze direction upon steering.

When participants fixated outside of the bend they understeered (i.e. steered in the direction of their gaze); however, when they fixated on the inside of the bend they did not oversteer significantly more than when they fixated in the middle of the road. This could be linked to a propensity to oversteer which has been observed previously in Robertshaw and Wilkie (2008) as well as in a number of other studies using different methodologies (e.g. Coutton-Jean et al., 2009; Gawron & Ranney, 1990). It is currently unclear why there is a propensity to oversteer but it could be linked with a conservative steering strategy (see Wilkie et al., 2010). Interestingly when modeling the steering trajectories we were able to capture this asymmetry by using a disproportionate increase in the weight of gaze angle as an input to α when road edges were faded.

As well as examining the biases caused by fixating on eccentric targets, we can also determine whether there is an impact of simply fixating when the road edges are degraded (rather than being free to look at the most informative point in the scene). We compared the steering error (RMS) for free-gaze (Experiment 1) and fixed gaze in the middle of the road (subset of Experiment 2) using a repeated-measures ANOVA with experiment as a two-level factor and road position as a three-level factor[7]. We found that Experiment 2 (Fixed Gaze) resulted in significantly larger steering errors than Experiment 1 (Free Gaze), $F(1,8) = 13.42, p = .006, \eta_p^2 = .63$. It can be concluded that when participants were given the choice of where to direct their gaze they performed better than when their gaze was fixed in the middle of the road. This reinforces the assertion of Wilkie and Wann (2003b) that active-gaze provides an advantage over tracking fixations when steering. Our study takes this further by showing that active gaze fixations can be used to compensate for degraded scene information. In Experiment 1 when we degraded or even removed road edges participants steering performance was not significantly affected (Table 1) whereas in Experiment 2 when gaze was restricted merely degrading the road edges did have a significant effect on steering (Table 2).

Crucially, we have seen that information from the direction of gaze is not the only factor affecting steering performance. When we model these data using flexible weightings of gaze direction and the road edges, a very good fit is achieved by weighting the road edge information more highly than gaze. This can be explained in terms of the demands of the task: the two road edges provided not only information regarding the future trajectory participants had to take, but also provided constraints to their trajectory, since they were instructed to stay within the road edges.

5 General Discussion

Our main experimental aim was to examine the sources of information that are used when controlling bounded high-speed actions. The first experiment investigated the effect of degrading/removing boundaries on gaze and steering when maintaining different lateral positions. The patterns of gaze and steering behavior we observed would not be predicted based on a single theory of steering control. As highlighted in the Introduction, actions can be generated purely based on feedback information. If this had been the case when steering bends, then we would expect no differences in gaze or steering behavior during inside and outside road position

[7] Road-position RMS was averaged across the visibility conditions. To make the means as comparable as possible we calculated the averages using only the visibility conditions that were presented in both experiments, and from Experiment 2 only the conditions with fixations in the center of the road were used.

conditions (under equivalent visual conditions). Instead, we observed steering errors that were asymmetric across road positions and gaze patterns were shifted, suggesting that prospective information was being used. The tangent point theory (Land & Lee, 1994) is predominantly driven by prospective information from the inside road edge (via extensive fixation of the tangent point). Our data is not consistent with the tangent point model: degrading/removing the outside road edge impaired steering, steering was still effective when the inside road edge was degraded/removed, and we did not observe extensive fixation of the tangent point. As predicted by the 'active gaze' model (Wilkie & Wann, 2002; 2003a; Wilkie et al., 2008) people usually sampled information by directing their gaze towards points in the world through which they wanted to steer (Figs. 5 and 6). Previously it has been observed that gaze tends to be used to sample from the middle of the road when trying to maintain a central position (Robertshaw & Wilkie, 2008; Wilkie & Wann, 2003b). The data presented here support the recent findings of Wilkie et al. (2010) suggesting that gaze is directed to a point on the road that lies on the desired future path, even if that position is offset relative to the road center. Gaze was, however, influenced by the removal of the inside or outside road edge (Fig. 5a) since it shifted towards the remaining visible boundary. This would not be predicted by the 'active gaze' steering model, because it reflects an interaction between the system trying to sample prospective information from gaze as well as feedback information from the periphery under sparse visual conditions. This relationship is clarified by modeling steering with both near road feedback and prospective components similar to the proposal of Salvucci & Gray (2004). The model we use, however, builds on the Wilkie et al. (2008) active gaze model to make use of redundant visual and non-visual inputs, and which can generalize to an open field setting where path information is unavailable.

A flexible and robust steering system would use both road edges to provide position-in-lane feedback. In line with this view, participants were still able to maintain a central road position when either road edge was degraded or removed (Fig. 4). There was, however, a significant interaction between road position and road edge visibility. When maintaining an offset lateral position the nearest road edge was most influential: errors were highest when trying to steer near to the road edge that was missing. We can conclude that when generating fast smooth trajectories that need to fall centrally within a bounded region both boundaries will be used, whereas the nearest boundary will be predominant if adopting an offset trajectory. This finding is consistent with the observations of Coutton-Jean et al. (2009) who used an elegant paradigm to examine steering down roadways with road edges that could be gradually displaced during trials. Coutton-Jean et al. (2009) concluded that it was only displacement of the inside ("interior") road edge that led to systematic biases in steering trajectories, however, they also noted that drivers adopted a position nearer to the inside edge (i.e. a tendency to oversteer). We suggest that the inside road edge may have been unintentionally predominant in their study because they were located near the inside edge. Our results suggest that the outside edge would also have played a role if the participants had been positioned nearer that edge. Of course it is possible that while both edges are used, the inside road edge is weighted more highly. Future work could consider whether displacing the inside or outside road edges have an equivalent effect on steering when positioned near each edge (when gaze is controlled).

As well as road position playing a role, the steering performance in Experiment 1 can be partially explained in terms of eye-movement patterns. In the conditions where participants tried to maintain their position far from the visible road edge they shifted their gaze partially towards the visible edge. Whilst this pattern of behavior is not explained by the active gaze model of steering, it is consistent with a need to reduce the eccentricity of the visible edge in peripheral vision (Fig. 5) and improve feedback information. This adjustment of gaze does not come without a cost, however, since the prospective information becomes compromised, and steering error increases dramatically (Fig. 4). Whilst there is usually a strong coupling between gaze direction and steering, examining steering under free-gaze conditions makes it difficult to establish whether steering behaviors are exhibited due to gaze patterns, or whether the recorded patterns of gaze merely reflect the steering trajectories that unfold (Robertshaw & Wilkie, 2008, Wilkie et al., 2010). In addition the effect of degrading road edge information may have been underestimated due to subtle alterations in gaze patterns that improved information sampling. To control for this, we carried out a second experiment that included fixation points positioned on or near the road. This allowed us to confirm the relative influence of prospective gaze direction information as the quality of road edge information degraded (with concomitant degradation of peripheral feedback information). The active gaze theory would suggest that these fixation conditions should cause systematic biases to steering in the direction of the fixation point. Generally there were indeed systematic steering biases resulting from the direction of gaze, and, as expected, this effect was most pronounced when the visual information from the road edges was weakest (Fig. 9b).

The importance of unrestricted gaze for controlling locomotor steering is also evident by comparing Experiments 1 and 2. Steering errors were lower overall when gaze was free (Experiment 1) than when fixating the road center (Experiment 2) and fading the road edges caused greater changes to steering patterns when gaze was fixed. Since the only difference between the two experiments was the gaze behavior of the participants, it appears that when participants were free to look where they wanted they were better able to sample prospective and feedback information to compensate for poor visibility. The active gaze model (Wilkie et al., 2008) has not previously been used in conjunction with peripheral visual information from scene features. Here, we found that neither gaze nor road edge visibility could explain the data adequately on its own. Instead our data reinforce the suggestion of Salvucci and Gray (2004) that near and far components are combined to supply the steering system with sufficient information to act within explicit boundaries. By incorporating a flexible weighted feedback signal into the active gaze model (alongside prospective gaze direction information) we can account for steering when there is a delineated path, as well as generalizing to cases where the path information is absent/degraded.

In conclusion, we have shown that when generating fast smooth actions along a bounded trajectory, both feedback and prospective information is used by the human perceptual-motor system. Both boundary edges can be used to provide feedback information whereas prospective information is sampled through systematic and directed gaze patterns. This is in line with the neuroimaging data of Field et al. (2007) and more recently Billington, Field, Wilkie, and Wann (2010), where different parietal regions seem to be involved with prospective (future path) and feedback aspects of steering control. As has been shown for other sources of information (Wilkie & Wann, 2002, 2003a, 2005) the human locomotor system seems to be able to use a weighted combination of information sources, with gaze direction information having a greater influence over steering when the delineated path is weak. Given some of the qualitative similarities between patterns of behavior when controlling hand movements (e.g. tracing paths) and locomotor trajectories (Hicheur, Vieilledent, Richardson, Flash, & Berthoz, 2005; Wilkie, Raw, Kountouriotis, & Mon-Williams, 2011) it will be interesting to see whether fast smooth hand movements along bounded trajectories are reliant upon a similar balance of information as that used during steering.

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