Does gaze influence steering around a bend?

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M. F. Land and D. N. Lee (1994) suggested that steering around a bend is controlled through the estimation of curvature using the visual direction of a single road feature: the tangent point. The aim of this study was to evaluate, using a simulated environment, whether the high levels of tangent point fixation reported by some researchers are indeed related to steering control. In the first experiment, gaze patterns were examined when steering along roadways of varying widths and curvatures. Experiment 2 investigated the effects of enforced fixation on steering, when gaze was directed to the road ahead at a range of lateral eccentricities, including the tangent point. All participants completed both experiments. Overall, there was no evidence for extensive tangent point fixation in the free-gaze experiment and enforced tangent point fixation did not result in more accurate steering. The present results seem to suggest that participants tend to steer in the direction of their gaze; hence, looking at the tangent point causes the driver to steer toward it. These results provide some support for the R. M. Wilkie and J. P. Wann (2002) model of steering, which proposes that drivers will direct their gaze toward points they wish to pass through.

Keywords: driving, gaze, steering, eye movements, tangent point


Introduction

Most activities that we engage in on a daily basis rely on accurate visual information for their execution; for such activities to be carried out effectively, movement of our limbs and body must be precisely controlled by information obtained through active exploratory gaze patterns (for examples, see Land & Hayhoe, 2001). Few actions controlled by vision carry with them such risks for ourselves and those around us as driving. In the UK, between 1994 and 2002, over one third of car occupant fatalities died in accidents at bends (Broughton, 2005), highlighting the importance of investigating the visuo-motor strategies used in these situations.

There are a number of possible informational sources that the visuo-motor system may rely on to control steering, such as retinal flow (either directly, e.g., Wann & Land, 2000, or through the recovery of heading, e.g., Fajen & Warren, 2003) and visual direction (e.g., Rushton, Harris, Lloyd, & Wann, 1998; Salvucci & Gray, 2004). A number of theories regarding how such information can be transformed into a steering command have been proposed; for example, Wilkie and Wann (2002, 2003b; Wilkie, Wann, & Allison, 2008) presented a model whereby certain classes of information act within a point attractor to push the system toward a particular state or trajectory. Wilkie et al. (2008) demonstrated that if an observer fixates a point, they wish to pass through their visual angle specifies, the degree and the direction of steering response necessary, while the rate of change of this angle indicates whether the observer is on an appropriate trajectory to pass through the point of fixation. Similarly, rotation components in the raw retinal flow field provide some information about the necessary steering response and whether the current trajectory will pass through the fixated point; hence, both visual direction and raw retinal flow provide the information needed to initiate and to modify a steering maneuver. Wilkie et al. (2008) argue that when fixating a point one wishes to pass through, the visuo-motor system acts to nullify the visual angle and/or any rotation component in raw retinal flow. There is redundancy in the information provided by visual direction and retinal flow, but this results in a robust steering system that can cope with changing environmental conditions. Wilkie and Wann’s model is an attractor to the point of fixation, the primary prediction being that during self-motion gaze will be directed to points in the world the observer wishes to pass through, with drivers tending to steer in the direction of their gaze.

An alternative model of steering control was proposed by Land and Lee (1994) who examined natural gaze patterns when driving along a tight winding road. Based on their observations, they proposed that road curvature is estimated from the visual direction of a single road ‘‘feature,’’ the tangent point. The tangent point is an optical property of the scene situated at the apex of the bend (see Figure 1A). Land and Lee examined gaze direction when moving at a

Received August 8, 2007; published April 23, 2008

doi: 10.1167/8.4.18
self-determined speed (on average around 40–45 km/h) along a single-track (3 m wide), one-way road with continuous and unpredictable bends. The 3 drivers spent up to 80% of the time during the first few seconds of a bend looking within 3° of the tangent point.

Land (1998) and Land and Lee (1994) outlined how the tangent point could be used to control steering, using the following equation (Equation 1):

\[ \text{Curvature} = \frac{1}{r} = \frac{\theta^2}{2d}, \]

where \( r \) is the radius of the curve, \( d \) is the distance to the lane edge, and \( \theta \) is the angle between the direction of heading and the direction of gaze (see Figure 1B). They proposed that \( \theta \) can be recovered from extra-retinal signals resulting from fixation of the tangent point since the driver’s body remains in line with the car’s current heading. In line with Dorges’ (1978) two-stage model of steering, Land (1998) and Land and Horwood (1995) propose that the tangent point provides a feedforward steering control signal, allowing the driver to match road curvature; feedback from the near road edges viewed peripherally provides a second control signal that is required for accurate lane positioning.

Using the model (Equation 1) proposed by Land (1998) and Land and Lee (1994), to control steering around a bend requires an estimate of your distance (\( d \)) from the inside edge of the road and would generate a constant curvature path that maintains a steady distance from the curb. Wann and Land (2000) suggested that limits to the precise detection of \( d \) make the tangent point strategy more useful as an approximation of bend curvature, which would require later verification, either through monitoring the motion toward or away from a road edge, or change in gaze angle over time (\( d\theta/dt \)). Use of the tangent point to control steering is only possible when there are clearly visible road edges; it offers no solution during open field steering where obstacles may be present, but continuous demarkation of path is absent.

Subsequent studies examining gaze patterns when steering around a bend have failed to replicate the propensity for tangent point fixation as observed by Land and Lee (1994). In a simulator study comparing free, fixed, and tracking gaze when steering along a single-lane curving roadway, Wilkie and Wann (2003a) found no evidence for a tangent point strategy. Participants in the free-gaze condition looked at the center of the road or a zone proximal to the center 80% of the time, with the proportion of inside road edge fixation ranging from 1% to 15% for individual participants. It also appears that tangent point fixation is not vital for curve negotiation. Land and Horwood (1995), in a study examining steering performance with only small sections of the simulated road edges visible, found that accurate steering did not rely upon the tangent point being displayed, though they did suggest that optimal performance would involve using this region of the road.

In order to evaluate which gaze strategies are used when steering, it is important to consider the methodological differences between the Land and Lee (1994) and the Wilkie and Wann (2003a) studies. Land and Lee used real, undulating roads, higher speeds, and blind (closed) bends. In contrast, Wilkie and Wann used open bends and point out that with closed bends it is difficult to distinguish between looking at the tangent point and looking through the tangent point to the road ahead; hence, on closed bends, tangent point fixation may actually reflect participants’ attempts to gain an optimal view of a distant point on the road ahead. However, in a study of tangent point fixation on rural roads Underwood, Chapman, Crundall, Cooper, and Wallen (1999) found that all drivers fixated the tangent point marginally less on closed than on open curves, suggesting that this methodological issue cannot account...
for the differences in recorded gaze patterns between Land and Lee and Wilkie and Wann. In addition, using a methodology more analogous to Land and Lee’s, with real roads and participant-determined speeds, Underwood et al. found that only around 12.6% of fixations were within 2° of the tangent point, a figure more in line with the results of Wilkie and Wann, again suggesting that the contrasting findings of Land and Lee and Wilkie and Wann cannot be accounted for by these methodological differences.

As we have discussed, tangent point fixation is one of a number of strategies that could be used to control steering. There is some evidence that the tangent point is fixated when negotiating bends; however, it has also been shown that tangent point visibility and fixation are not essential for adequate steering (Land & Horwood, 1995). Whether the high levels of tangent point fixation found in some studies (e.g., Land & Lee, 1994) are actually related to steering control is unclear since the tangent point strategy has not been examined through robust experimental manipulation. The aim of this study is to revisit where people look when steering round bends and to investigate whether enforced fixation of different road areas has an impact on steering. First, we examine free-gaze behavior and steering when negotiating bends of varying width and curvature. Adjusting road width will have the greatest impact on the peripheral view of near road edges and less of an influence over visual information from the road ahead. In contrast, altering road curvature primarily affects the far road information available to the driver, with the peripheral view of the scene being affected less. In line with a two-stage model of steering control (e.g., Donges, 1978), we would expect that altering road width would primarily impact feedback information from near road edges, while changing road curvature may have a greater impact on far road feedforward information. We then examine the impact of enforced fixation at varying lateral eccentricities, employing the same roadways as in the free-gaze condition. Tangent point fixation should result in accurate lane following if the Land and Lee model holds true, whereas the Wilkie and Wann model of steering would predict that enforced fixation on the tangent point would result in oversteering and cause paths which cut the corner more than when fixating the center or outside edge of the road. The Wilkie and Wann model also predicts a systematic pattern of biases based on gaze fixation location consistent with steering toward the point of gaze.

### General method

#### Participants

Nine participants (5 females, 4 males; aged 20 to 57, mean 26.5 yrs), all having normal or corrected-to-normal vision, took part in both Experiments 1 and 2. Participants held a full UK driving license and had at least 1 year of regular driving experience post driving test. All participants gave their informed consent prior to their inclusion in the study, which was approved by the relevant local ethics committee (University of Leeds).

#### Apparatus

The platform was a PC (Pentium(R) 4 CPU 3.20 GHz), running tailor made software with Direct X libraries in Windows XP. Images were generated at a frame rate of 50 Hz and projected onto a large screen (1.98 × 1.43 m), viewed from a distance of 1 m, therefore subtending a total visual angle of 89.42° × 71.31° and filling the majority of the participant’s field of view. The projection system was a Sanyo Liquid Crystal Projector (PLC-XU58).

The participant was seated in a racing-style driving seat, height adjusted for each individual such that eye height was 1.05 m from the ground. Mounted in line with the seat was a force-feedback steering wheel (Logitech Momo Racing), which provided the participant with control over their direction of motion in the range: −32.8°/s to 32.8°/s. Rotation of the wheel increased the rate of change of heading with a minimum step size of 0.36°/s. Steering changes were applied to the simulated direction of motion as though rotated on a point, with no application of vehicle dynamics. The steering wheel supplied data at the same rate as the 50-Hz display; therefore, the maximum delay between movement of the steering wheel and screen position update was 20 ms. The interior of the experimental booth was matt black; all incidental light was excluded.

The participant’s eye movements were recorded using a head-mounted eye-tracking device (ASL Model 501; sampling rate 50 Hz; system accuracy 0.5° visual angle; resolution 0.1° visual angle). This system uses an infrared camera to determine the position of the pupil and the corneal reflection (CR) of the eye; the separation between these two points varies with eye rotation; hence, pupil/CR separation is used to determine point of gaze with respect to the head. The eye tracker was calibrated for each participant using a regularly spaced 9-point grid (24.23° × 18.26°) displayed on the projection screen, such that the center of the calibration grid was located in the center of the participant’s field of view.

A head tracking system (ATC Flock of Birds) recorded the participant’s head movements. This system transmits a pulsed DC magnetic field; a sensor attached to the participant’s head computes its position and orientation relative to the transmitter, using the measured magnetic field characteristics. Eye and head position data were integrated using ASL Eyehead Integration software to compute accurate point of regard, which was then recorded in synchrony with the steering input. The experimenter also had a monitor where they could view point of gaze superimposed onto the computer-generated scene.
Stimuli

The visual environment contained a ground plane textured with a seamlessly tiled gravel bitmap, which was clipped in software at a distance of 80 m from the participant; this meant that the horizon was 1° below the true horizon (see Figure 6). A roadway was generated by rendering two green edges superimposed on top of the textured ground plane. The shape of the road comprised a 16-m (1.2 s) straight section (to avoid the need for an immediate steering response), followed by a single bend of constant curvature generated using the formula of a circle:

\[ r^2 = (x-h)^2 + (z-k)^2, \]

where \( r \) = radius of the circle, \( h \) = radius adjusted by the road width, and \( k \) = road width. A total of four distinct roadways were generated, using two levels of curvature combined with two road widths. Roadway direction to the right or left of the start position was chosen randomly for each trial. Observers traveled at a constant speed of 13.8 m/s (50 kph/31 mph) and were located in the center of the roadway at the beginning of each trial.

Roadways with curvatures of radius 60 m and 120 m (referred to as R 60 and R 120 henceforth) provided challenging and gentler curvature conditions, respectively. On UK roads, the limiting radius for standard two-lane carriageways of design speed 50 km/h (31 mph) is 90 m, as stipulated by the Design Manual for Roads and Bridges (Department of Transport, 1994); hence, a curvature 33% below the limiting radius (since there was no need to consider road safety issues within our simulated environment) was chosen as a challenging steering condition, and 33% above the limiting radius was used as a gentler curvature.

The two road widths used were 3 m and 6 m (referred to as W3 and W6 henceforth): 3 m corresponds to the width of Queen’s Drive, the road used in Land and Lee’s (1994) study (as described in Land & Horwood, 1995), and is the minimum lane width used on UK two-lane carriageway roads (Department of Transport, 1994). A 6-m road, which is wider than the maximum carriageway width permitted on UK roads (Department of Transport, 1994), was also selected.

Two experiments were carried out with differing gaze fixation requirements. Details of these are given in the individual methods.

Procedure

Before participating in the experiments, an initial practice phase consisting of 3 × 37.5 s trials of steering along a gently curving sinusoidal roadway at a constant speed of 8 m/s (29 kph) served to familiarize the participant with the apparatus and visual environment. Each experimental trial lasted approximately 10 s.

Experiment 1: Free gaze

Method

In the free-gaze condition, participants could look wherever they wished in the scene. A block of 24 free-gaze trials was presented, comprising the 4 roadway conditions (2 widths and 2 curvatures with 6 trials of each) displayed in a random order. Participants were instructed to steer as close to the center of the roadway as possible. Point of gaze on the projection screen was recorded, from which gaze location on the simulated roadway was extrapolated. Deviation of gaze from the center of the road was calculated for each frame of each trial, providing a measure of gaze bias. In the cases of 2 participants, the data were inadequate for gaze analysis purposes due to problems with achieving an adequate eye image; therefore, their gaze and steering data were removed from the free-gaze analysis.

The position of the participant in the road was also recorded, and the deviation from the center of the road was calculated for each frame of each trial, providing measures of steering precision (RMS) and bias (constant error). All steering and gaze analyses were performed on the entire 9 s of constant curvature (i.e. with the straight section of the road excluded), unless otherwise stated. In addition to examining mean gaze bias, we also binned gaze fixations to generate a measure of the proportion of time participants spent looking within each of a number of fixation zones. We followed a similar procedure to examine steering by calculating the length of time spent in each roadway zone. Binned data allow a rapid and straightforward visual examination of the distribution of gaze/steering across the road; clearly, this provides an additional richness to the analysis that is not available from just focusing on averaged precision or bias. However, binned data, by encompassing a range of lateral eccentricities, tend to be less precise than bias/RMS data.

Results and discussion

Gaze analysis

Overall bias of gaze toward the inside or outside of the bend is captured by the mean constant error from the road center (see Figure 2). A two-way repeated measures ANOVA revealed that gaze was significantly more biased away from the center of the road on wider roads (\( F(1,6) = 41.82, p < .01 \)). There was no significant main effect of road curvature on gaze bias.
Binned data (see Figure 3) also highlights the general bias of gaze toward the inside of the bend on all roadways, though it is apparent that the majority of time was spent looking at the center of the road and the region between the center and the inside edge. A relatively small proportion of time was spent looking in the tangent point zones of each roadway (W3 R60: 20%; W3 R120: 16%; W6 R60: 9%; W6 R120: 7%), much less than the 80% reported by Land and Lee (1994). Participants looked toward the tangent point significantly more on 3-m-wide compared with 6-m-wide roads ($F(1,6) = 10.51, p < .05$); there were no significant differences in the level of tangent point fixation based on curvature.

Land and Lee (1994) suggested that the highest proportion of tangent point fixation can be found in the initial stages of a bend. Gaze patterns for the first 2 s of the bend were therefore examined for each roadway; Figure 3 indicates that gaze patterns across the first few seconds of the bend were very similar to those averaged across the entire bend, suggesting that averaging across the entire bend did not underestimate the level of tangent point fixation.

**Steering analysis**

Overall steering bias toward the inside or the outside of the bend is captured by the mean constant error (see Figure 4A). A two-way repeated measures ANOVA indicated that participants exhibited significantly greater oversteer on wider ($F(1,6) = 69.67, p < .001$) and more curvy roads ($F(1,6) = 23.29, p < .004$).

Root mean squared (RMS) deviation provides an overall measure of steering precision: Figure 4B indicates that participants’ steering was more precise on narrower roads. Road curvature appears to have had a greater impact on steering precision on the wide compared to the narrower road.
roadways. This apparent interaction can be explained by the relative levels of bias evident on the two road widths; on the 3-m-wide roads, participants displayed very similar levels of bias regardless of road curvature, but in opposite directions, and this is reflected in broadly equivalent levels of steering precision across road curvatures. In the case of 6-m-wide roads, the impact road curvature had on steering bias was similar in magnitude to its impact on 3-m-wide roads, but on 6-m roads this resulted in greater oversteer on R 60 m compared to R 120 m.

In a manner comparable to the gaze analysis, the amount of time spent in different zones of the road was also examined. Figure 5 indicates that participants successfully remained within the road edges on all roadways. On W3 R120, participants spent 75% of the time in the four zones (±0.375 m) around the centerline (shown on the graph as white/white hatching). The proportion of time spent in this central area decreased as bias toward the inside edge increased, with participants spending approximately 55% of the time in the central area on roadway W3 R60, 25% in this area on W6 R120, and 7% in the central area on W6 R60. This decreasing percentage of time spent in the central zone could indicate an increase in task difficulty across these four roadways.

Examining gaze strategies and steering behavior in free-gaze conditions across the four roadways provides a baseline measure for comparison with the experimental conditions. However, such observational data make it difficult to infer the causal direction of the effects. In free-gaze situations, it is likely that gaze and steering form a reciprocal relationship, resulting in a “feedback loop.”

Figure 4. Mean deviation of free-gaze steering from the centerline for each roadway condition. (A) Mean bias (constant error) of steering from the road center (positive figures reflect bias toward the inside of the bend; negative figures reflect bias toward the outside of the bend). (B) Steering precision (root mean squared error). Error bars = standard errors.

Figure 5. Free-gaze steering, proportion of time spent in each region of the road. All zones are 0.375 m wide: the center zones (either side of the centerline) are each divided into two zones of 0.1875 m, highlighted in white and with white hatching.
Hence, in order to isolate the specific impact of gaze on steering, it is necessary to vary the roadway parameters and gaze systematically.

**Experiment 2: Gaze fixation**

In the second experiment, we wanted to examine whether enforced gaze fixation at a variety of lateral eccentricities could cause systematic changes to steering behavior. The Wilkie and Wann model of steering predicts that fixation on one location should facilitate steering toward that point. In contrast, the Land and Lee model would suggest that fixing on the tangent point would result in accurate steering along the center of the roadway.

**Method**

In all fixation conditions, a single cross was superimposed onto the scene (see Figure 6). There were five possible fixation-cross locations: on the (invisible) centerline of the road and at 1.5-m intervals from the centerline toward both the inside and the outside road edges. There were 20 conditions (5 tangent point tracking fixation points × 4 roadways) presented in 3 blocks of 60 trials each: 2 trials of each condition in each block (some additional conditions were presented that are not reported here). All conditions were randomly interleaved within each block of trials. Participants were instructed to fixate the cross throughout each trial, and the steering task was to stay as close as possible to the center of the roadway. The gaze of each participant was monitored during data recording to ensure that the fixation conditions were adhered to, and all nine participants were observed to fixate the target points consistently and accurately. To verify fixation, we calculated the average offset of gaze from the centerline for each fixation condition on each roadway. The gaze data were consistent with accurate fixation on points that lay 1.5 m apart, with an average gaze offset of 1.57 m in line with this a two-way repeated measures ANOVA revealed a main effect of fixation location on gaze bias (F(4,28) = 115.82, p < .001); however, there were no differences in this pattern across roadways.

The fixation point located on the inside edge of each road tracked the tangent point, its position being recalculated for each frame of each trial, based on the participant’s lateral position in the road. If the observer is located on the centerline of the road, the distance ahead of the tangent point is a function of the curvature and the width of the road: being closer on more curvy and narrower roads. The distance ahead of the tangent point also varies as a function of the observer’s position in the road, moving further ahead as the observer steers toward the outside edge and closer as the observer steers toward the inside edge. The average distance ahead of the fixation point was 18.2 m (1.3 s), and at all times it remained within the optimum range of look-ahead distances for picking up curvature information (proposed by Land and Lee, 1994, to be 1–2 s ahead). All other fixation points were displayed at the same distance ahead as the tangent point, only laterally offset.

To examine the impact of gaze constraints on steering, the deviation of road position from the (invisible) centerline was calculated for each frame of each trial. Again, root mean squared (RMS) deviation and mean constant error (CE) provided measures of precision and bias for each fixation condition on each roadway.

**Results and discussion**

*Patterns of steering across roadways independent of fixation location*

First we examined steering across roadways independent of gaze fixation location (averages of steering bias and precision across all five fixation locations). This pattern (see Figure 7) reflects the baseline pattern observed in the free-gaze condition (Figure 4). A two-way repeated measures ANOVA indicates that participants’ steering was significantly more positively biased (oversteer) on wider (F(1,8) = 41.10, p < .001) and more curvy (F(1,8) = 7.79, p < .05) roads. This consistency across free-gaze and fixation conditions indicates that there was a baseline impact of the road properties irrespective of fixation condition.
Patterns of steering across fixation locations independent of road curvature

We then examined steering across fixation locations independent of road curvature (see Figure 8; averages of steering bias and precision across roadways of the same width). The bias data (Figure 8A) for 6-m-wide roads indicate a general pattern of participants tending to steer in the direction of their gaze, with participants increasingly steering toward the inside edge of the road as gaze progressed toward the inside edge. The steering precision data for 6-m-wide roads (see Figure 8B) display a slight trend toward increased precision with decreasing bias. On the 3-m-wide roads, fixation location appears to have had little impact on steering bias or steering precision. Figure 8 also highlights that on 3-m-wide roads participants on average exhibited less bias and greater precision in their steering than on 6-m-wide roads. As noted above, altering road width has the greatest impact, perceptually, on the driver’s peripheral view of the near road edges. Hence, these results suggest that the stronger feedback information available on narrower roads ameliorated the impact of fixation location on steering and engendered better steering precision and bias. These findings support a 2-stage model of steering control as proposed by Donges (1978) and Land and Horwood (1995).
Steering precision and bias for each fixation location on each roadway

Three-meter-wide roads

Figure 9A illustrates that on W3 R60 there was generally a slight tendency toward steering in the direction of gaze. W3 R120 displays the opposite pattern, with increasing bias toward the outside of the bend as gaze progressed toward the inside road edge. One-way repeated measures ANOVAs for W3 R60 and W3 R120 revealed no main effect of fixation on steering bias for either roadway. In addition, one-way repeated measure ANOVAs for the W3 R60 and W3 R120 roadways indicate that there was no main effect of fixation location on steering precision for either roadway. These precision and bias results support the assertion that on the 3-m-wide roads steering was quite robust to variations in fixation location, even when the fixation points were eccentric to the road edges.

Six-meter-wide roads

On the 6-m-wide roads, fixation location had a greater impact on participants' steering. Figure 9B indicates that on W6 R60 participants' steering was increasingly more biased toward the inside of the bend as gaze progressed from the outside to the inside road edge; however, this trend appears to tail off slightly at the extremes of fixation location as participants looked at the road edges. A one-way repeated measures ANOVA revealed a significant main effect of fixation on steering bias ($F(4,32) = 15.38, p < .001$). Polynomial contrasts revealed a significant linear trend ($F(1,8) = 25.68, p < .001$); this indicates that bias increased steadily as gaze fixation progressed toward the inside of the bend. With a baseline of bias toward the inside of the bend across both free-gaze and fixation conditions, this linear trend appears to reflect participants tending to steer in the direction of gaze; in the case of the fixation points toward the outside edge of the road, this tendency resulted in participants being drawn toward the road center. Planned contrasts comparing the center fixation point to both the inside and the outside road edge fixation points revealed that steering was significantly more biased toward the inside of the bend as participants fixated the inside road edge compared to the center fixation point ($F(1,8) = 8.31, p < .025$) and was significantly more biased toward the outside of the bend as participants fixated the outside road edge compared to the center fixation point ($F(1,8) = 14.29, p < .01$). Figure 10 illustrates the steering patterns of two representative participants for a 1.5-s section of the W6 R60 roadway. This highlights steering bias in the direction of gaze at the individual level. A one-way repeated measures ANOVA revealed no main effect of fixation condition on steering precision.

As illustrated in Figure 9A, on W6 R120 there was a general trend of increased steering bias toward the inside of the bend as gaze progressed from the outside toward the inside road edge. However, when the fixation point was located on the inside or outside road edge, this general trend was reversed, with the level of bias returning back in toward the level exhibited in the case of the center fixation point. A one-way repeated measures ANOVA indicated a main effect of fixation on steering bias ($F(4,32) = 6.23, p < .05$). Examination of polynomial contrasts revealed significant linear ($F(1,8) = 6.66, p < .05$) and cubic ($F(1,8) = 21.31, p < .01$) trends. The pattern of bias observed in Figure 9A appears to be best summarized as a combination of linear and cubic trends, hence highlighting the general linear element of fixation in the direction of gaze, but also the significance of the impact of the road edges on steering bias. Planned contrasts revealed no significant differences in bias between the center fixation point and either of the road edges. In the case of W6 R120, there was a slight trend toward decreasing steering precision as gaze moved away from the centerline toward the road edges. However, a one-way repeated
measures ANOVA revealed no main effect of fixation condition on steering precision.

The proportion of time spent in different regions of the roadway was also examined. As Figure 11 illustrates, in all cases participants managed to steer within the roadway edges. In general, across all fixation conditions on the same road, steering was distributed across the same lateral zones, the only variation being the relative proportion of time spent in each of those zones. Comparison to Figure 6 highlights the fact that for each roadway, steering was...
broadly distributed across the same lateral zones in the fixation and free-gaze conditions. Hence, for each road width, there was a consistent region of the road that steering was restricted to, regardless of fixation location; this reinforces the overall consistency of steering on each roadway despite the variability based on fixation location.

**General discussion**

The principal aim of this study was to examine the impact of gaze fixation on steering around a bend. In particular, we wished to evaluate the applicability of the tangent point model of steering control proposed by Land and Lee (1994) compared to the predictions of the Wilkie and Wann (2002, 2003a; Wilkie et al., 2008) model of steering. The first experiment examined free-gaze patterns when steering around roads of different widths and curvatures. We found that gaze was predominantly directed toward the center and the inside of the bend, and while some fixations were observed in the region around the tangent point, the proportion of these fixations was at most 20% (consistent with Wilkie & Wann, 2003b). Steering behavior reflected gaze behavior, in that we generally observed oversteer when gaze was directed most toward the inside of the bend. This suggests a direct link between the direction of gaze and the direction of steering. To examine the causality of this effect, we carried out a second experiment where we enforced gaze fixation at specific lateral eccentricities with respect to the road, including fixating the center of the road and the tangent point. Fixating the tangent point zone did not cause a significant improvement to steering compared to other fixation zones, rather the general pattern of steering errors suggests that participants took paths that were biased toward their point of fixation, including bias toward the tangent point when required to fixate on it.

It is worth briefly considering whether we failed to observe use of the tangent point strategy because of properties of our simulated environment. Land and Lee (1994) suggested that tangent point fixation would be particularly evident in more challenging steering conditions, citing narrower roads as one example (p. 743). We tried to design the task to provide favorable conditions for use of the tangent point by implementing a relatively high locomotor speed (31 mph) as well as a range of roads that included a challenging narrow and tight bend (W3 R60). Varying roadway parameters allowed an examination of the tangent point strategy under contrasting road situations. The task positioned the participant in the middle of the road at the beginning of each trial, and they were required to maintain this position throughout the trial. This should have been particularly suited use of the tangent point strategy, which provides a solution for steering a constant curvature path at a known distance from the roadway edge. Despite such favorable conditions, participants did not adhere closely to the tangent point strategy across any of the roadways used in our study. Although real-world roads do not typically have extended constant curvature bends, smaller subsections these bends do remain essentially constant. While the bends we employed are useful for investigating steering performance under controlled experimental conditions, it is possible to imagine drivers making a single perfect steering maneuver as they enter the bend, thus eliminating any need to make further corrective adjustments. Such perfect steering was not, however, observed in the present studies, possibly because of the challenging steering conditions used.

We did observe changes in the amount of tangent point fixation on roads of different widths: When steering along the 3-m-wide roadways, participants exhibited greater tangent point fixation than on the 6-m-wide roads. We suggest, however, that this was not linked to task difficulty since we observed no change in tangent point fixation on roads of different curvature and even on the narrower roads percentage of time looking around the tangent point (±1.2°) was still only ~18%, much less than the 80% previously reported by Land and Lee (1994). It is likely that the increase in tangent point fixation on narrow roads was linked to a reduction in the possible range of fixation zones, which would naturally result in an increased proportion of gaze fixations falling within regions near to the tangent point.

In Experiment 2, we asked each participant to direct their gaze toward a fixation point at one of five lateral eccentricities. On wide tight bends when fixating the tangent point, participants’ steering was significantly more biased toward the inside edge of the road than when fixating the road center. When fixating the outside edge, participants exhibited bias in the opposite direction to tangent point fixation, suggesting that gaze direction does indeed alter steering. The overall trend across fixation locations on wide tight bends indicates that participants tended to steer in the direction of their gaze, in line with the predictions of the Wilkie and Wann steering model, which embodies the idea that participants will steer toward where they look. This model is explicitly an attractor to the point of fixation and as such can successfully account for the tendency of participants in this study to steer in the direction of gaze. Crucially, this provides participants with the option of taking any curved path they wish around the bend and therefore can account for the full range of steering strategies exhibited by drivers.

There were two interesting situations which moderated the effects of gaze upon steering. Firstly, steering bias did not increase linearly with fixation eccentricity; instead, the extreme fixation points caused similar biases to mid fixation points. This pattern could be interpreted as saturation of steering bias in a similar way to that reported by Readinger, Chatziastros, Cunningham, Büllhoff, and Cutting (2002), who studied the impact of directed gaze.
on a straight road; however, the lateral fixation eccentricities used in our conditions were much smaller than those used previously. Secondly, on the narrower roads where the peripheral view of the road edges was strongest, we only saw weak changes in steering bias based on fixation location. A 2-stage model of steering (e.g., Land, 1998; Land & Horwood, 1995) would suggest that near road edges provide feedback information about position in lane, whereas a more distant point on the road provides feedforward information about upcoming road curvature. It seems that a weighted combination of these two types of information can describe our data well. For example, wide roads provided the weakest feedback information, tight bends provided the strongest feedforward information, and as a result gaze fixation had the largest influence when steering down wide tight roads. On narrow gentle bends, the balance of feedback and feedforward information is reversed, and the influence of gaze fixation over steering was at its weakest. The idea that a feedback signal from peripheral road information can inform steering control is not incompatible with the Wilkie and Wann model since the model relies on a variety of sources that can be both retinal and extra-retinal in nature (Wilkie et al., 2008). Recent neuroimaging evidence supports a distinction between the processing requirements for feedforward and feedback information when steering, with distinct parietal regions being implicated for each type of information (Field, Wilkie, & Wann, 2007). Feedforward information can also be functionally divided since the control of eye movements during steering selectively activates the parietal eye fields (PEF) whereas processing “future path” information independent of eye movements activates a region anterior to the PEFs, tentatively labeled the parietal path area (Field et al., 2007). A clear direction for future research is to determine how a number of sources of peripheral information can be integrated with visual information that is modulated by gaze direction and how these processes are supported by parietal brain regions.

It should be noted that irrespective of fixation condition, wider and curvier roads increased participants’ tendency to oversteer, despite being asked to maintain a course along the center of the road. This pattern is in line with studies investigating real roadway situations where it has been shown that drivers generally use a corner-cutting strategy when negotiating bends (Glennon & Weaver, 1971, cited in Gawron & Ranney, 1990), a pattern that is more pronounced on tighter curves (Emmerson, 1969, cited in Gawron & Ranney, 1990). We propose that the increased oversteer on our tight roads is caused by a natural tendency to revert to a preferred and habitual steering behavior. Insufficient steering (understeer) will cause a driver to leave the road more quickly on tighter bends, and so oversteer can compensate for this by increasing the amount of road available to invoke corrective steering actions. Combined with the natural tendency to oversteer, wider roads provide greater scope for lateral motion, and so we see greater incidences of corner cutting in these cases.

In contrast, a more straight line path can be taken around gentler bends with less risk and so a reduction in oversteer (or even understeer) can result.

In line with the results of this study, advanced driving advice, relating to both motorcycles (e.g., Motorcycle Safety Foundation, 1992) and cars (e.g., Bondurant & Blakemore, 1998), recommends that drivers should look where they want to go. In many situations (on open bends) this approach is incompatible with the tangent point strategy since fixating the tangent point would cause the driver to steer toward it, rather than match the curvature of the road. As noted in the Introduction, the visuomotor strategies involved in steering are a particularly important area of research given the high risks involved in driving. We contend that the present results support the advice given by advanced driving instructors that drivers should be encouraged to look ahead on the road to where they want to go.

Acknowledgments

Robertshaw completed this research while being funded by a Nuffield Foundation Student Bursary and later by an EPSRC doctoral training grant. Thanks to John Wann for input to earlier presentations of this work and for the loan of the head-tracker (ATC Flock of Birds) and other equipment purchased on EPSRC UK grants GR/S86358/01 and EP/D055342/1. Thanks also to Andrea Utley for the loan of the head-mounted eye tracker (ASL 501) and to Stephen Oliver for help in setting up the eye-tracking system.

Commercial relationships: none.
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