Driving around bends with manipulated eye-steering coordination

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This study investigated the link between drivers’ gaze positioning and steering behavior when negotiating bends. This was conducted by directing the driver’s point of gaze toward a target situated in the vicinity of the tangent point (TP), a region known to attract a significant amount of ocular fixations and thought to provide some useful input for anticipatory steering (M. F. Land & D. N. Lee, 1994). The orientation of gaze relative to the TP was manipulated and the resulting steering behavior was compared to that obtained with a free-gaze strategy. The data revealed that constraining eye movements did not impair steering behavior. On the contrary, the continuous tracking of the fixation point promoted smoother steering control, irrespective of the position of that point. This confirms that previewing the road curvature by tracking a distant point contributes to the stability of steering. The direction of the TP does not appear to be an essential parameter in that process (D. D. Salvucci & R. Gray, 2004). The results also indicate that continuously looking at the TP or further inside the bend yielded a deviation of the trajectory. This is consistent with the hypothesis that drivers look inside the lane boundaries to determine the future path (R. M. Wilkie & J. P. Wann, 2006).

Keywords: vision, sensorimotor control, driver models, tangent point steering


Introduction

Driving is a special form of locomotion. Most probably, it relies on those basic mechanisms that govern the perception of self-motion, such as the perception of the velocity flow field. However, apart from the fact that driving involves travelling at much greater speeds than human perceptual systems evolved to perceive, driving has some particular constraints. These make it a very different task from walking or running. When walking towards a target, people tend to turn onto a straight path in order to align the direction of heading and the retinal focus of expansion with the target (Warren & Fajen, 2004). On the other hand, a car can only adopt a curved trajectory. Roads are designed to reflect this constraint and are also delimited in width. Thus, drivers are required not only to match the road curvature but also keep a proper distance from the lane edges. Lane markers act not only as spatial constraints but also provide some useful visual cues for directional control and lateral motion. This is particularly evident when driving at night and using the white delineation of road edges. These singularities of the driving task ultimately explain why specific models of visual steering control are needed.

One of the most influential models of steering behavior was put forward by Donges (1978). This model describes the control of steering as two parallel processes, fed by different visual signals. The first level relies on close visual information (a few meters ahead of the vehicle) and contributes essentially to the fast correction of lateral position errors. The second level is fed by more distant visual information (about 2–4 s down the road) and is responsible for anticipating the changes in road curvature. Experimental results support this two-level control model. For instance, land and Horwood (1995) studied the behavior of drivers who negotiated a winding road with a view that was restricted to a small horizontal section of the road (1° of visual angle in height). When only the distant part of the road was visible, the curvature of the road was globally respected and driving was smooth, although some large lateral excursions from the center of the road were observed. Conversely, when only the near part of the road was seen, the trajectory was jerkier. The driver did succeed, however, in keeping the vehicle close to the road center. When both a near and a distant section were presented, driving performance was equivalent to a control condition where the whole road was visible. What Donges (1978) does not specify is the nature of the visual signals that feed both control processes. It can reasonably be argued that fast corrective control relies on driver perception through peripheral vision of both lane edge lines at a short distance from the vehicle. The nature of the anticipatory control is a more complex question. It is described by Donges (1978) as an open-loop process, fed by the “desired” path curvature.

Using gaze-tracking techniques, Land and Lee (1994) clarified the nature of the gaze strategies that are used to
preview oncoming road curvature. When approaching and negotiating a bend, the driver spends a significant amount of time looking in the vicinity of the tangent point (TP), i.e., the point where the direction of the inside edge line seems to reverse from the driver’s viewpoint. As such, it is not a fixed point on the curve in space but moves along the edge of the road as the driver passes through the curve. According to Land and Lee (1994), the direction of the TP can be used to estimate the curvature of the road without having to make a judgment of absolute distance. This is because of the simple geometrical relationship that exists between the curvature of the bend and the angle between that point and the direction of heading: 

\[
\frac{1}{R} = \frac{\theta^2}{2d},
\]

where \( R \) is the radius of curvature, \( \theta \) is the angle between the direction of heading and the direction of the TP, and \( d \) is the lateral distance to the inside edge line (Figure 1A). Thus, looking in the direction of the tangent point may be the best way of “reading” the curvature of the road at the sensorimotor level. This could provide an input signal to the motor system in charge of steering control (Land, 1998, 2001).

Boer (1996) put forward a model that also emphasizes the role of the TP but does not rely on the estimation of the curvature of the previewed oncoming bend. Instead, the model calculates an optimal trajectory on the basis of the distance and direction of a target point close to the TP but on the road (Figure 1B). The distance of this target point from the lane edge depends on the longitudinal distance of the TP from the car. It lies in the middle of the driving lane if the TP is more than 30 m ahead of the car (when approaching a bend, for instance), close to the TP (about half a car’s width into the road) if the TP is less than 20 m ahead of the car, or in an intermediate position if between the two. The key point of this model is that looking at control points along the future path allows an optimal trajectory to be computed. This minimizes the curvature of the trajectory and the resulting lateral accelerations, a commonly observed strategy for most drivers (Reymond, Kemeny, Droulez, & Berthoz, 2001). Although it does not involve the perception of the optic flow, this model is consistent with the observation that if the driver directs his gaze where he wishes to go, the curvature of the projected retinal flow along the future path will provide some information about steering errors (Kim & Turvey, 1999; Wann & Land, 2000; Wann & Swapp, 2000).

Salvucci and Gray (2004) propose a two-level control model of steering. This model is similar to that developed by Donges (1978) but it does not rely on the estimation of the road curvature or even more complex constructs, such as the intended trajectory. Instead, they propose a model based solely on the perception of the direction of two distinct points (Figure 1C). A near point corresponds to the lane center at a short distance ahead of the vehicle. It does not require ocular fixation and can be perceived via peripheral vision as the mid-position between both lane edges. A distant point may be the vanishing point when driving down a straight road or any salient point in the visual scene when negotiating bends, such as the TP or, if present, a lead car. The control law can be modelled by a standard proportional-integral controller that minimizes the changes in direction of the near and far points and keeps the angle to the near point close to zero. While both control points contribute to lateral stability, the far point determines anticipatory steering maneuvers and the near point is used to maintain an adequate mean position on the road. This means that the best gaze strategy for steering control in bends is to fixate any salient point that follows the road at a large enough distance ahead. The TP is a good candidate for this because it can be easily isolated in the visual scene. However, its angular position relative to the car heading is not a critical factor. In other words, the TP is convenient, but if there is another target moving down the road, the driver can use it the same way.

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**Figure 1.** The use of the tangent point according to (A) Land and Lee (1994): The emphasis is put on the relation between the direction of the TP and the curvature of the bend; (B) Boer (1996): Target points along the future path are used to compute an optimal trajectory; (C) Salvucci and Gray (2004): The change in direction of any salient point along the road can be used to achieve proportional control of steering.
The general objective of the present experiment was to contribute to a better understanding of the role of gaze positioning in the vicinity of the TP when negotiating a bend. The paradigm required subjects to continuously look at a visual target while driving. The target was either directly over the TP, or situated near to the TP with a constant lateral offset. The effects of gaze positioning on several indicators of driving performance were analyzed and compared with a control condition where gaze was unrestrained. Independently of any theoretical consideration, one can reasonably expect that, in the control condition, drivers will use the (supposedly optimal) gaze strategy acquired through past driving experience. Moreover, the more the constrained gaze moves away from the usual gaze positioning, the more steering will be altered. This hypothesis is supported by previous research which showed that preventing the driver from freely sampling the visual scene resulted in inaccurate steering (Marple-Horvat et al., 2005; Wilkie & Wann, 2003). Wilkie and Wann (2003), in particular, compared drivers’ steering behavior in three experimental conditions: free-gaze (no gaze constraint), tracking gaze (a fixation target was positioned 16 m ahead of the vehicle, at the center of the road), and static gaze (motion of the eyes was prevented by looking at a fixation target positioned straight-ahead). The participants were moved forward at a constant speed and were instructed to keep the vehicle close to the road center at all times. The results showed that the best performance occurred in the free-gaze condition, whereas steering severely deteriorated in the fixed-gaze condition, as evidenced by a mean constant error in lateral positioning and an increased variability of the trajectory. In the tracking gaze condition, the performance was close to the free-gaze condition, although a small constant deviation of the path from the centerline was observed. This study supports the idea that eye-steering coordination is essential in driving. Tracking the curvature of the road ahead is an essential part of this process and an active control of gaze appears to be beneficial. The present experiment was similar to that carried out by Wilkie and Wann (2003) in the sense that the drivers were prompted to track the road ahead by means of a fixation target. There were, however, two essential differences. First, the participants were given control over their speed and were free to use the full width of the driving lane; that is to say they could cut the corners if they wished to do so. Cutting the corners and adjusting speed are two essential components of negotiating bends, both of which may be influenced by manipulating eye-steering coordination. Second, the position of the fixation point was not fixed but was entirely determined by the dynamics of the TP in the visual scene. The aim was to promote a continuous “tangent point steering” strategy in a strictly defined way when looking at the TP proper and in a looser way when the fixation point was laterally shifted but was still animated by the dynamics of the TP. If glances in the direction of the TP are used to estimate the curvature of the road, as initially proposed by Land and Lee (1994), ensuring a continuous tracking of that point may improve the control of steering. Alternatively, diverting the driver’s gaze from the TP could result in oversteering or understeering, depending on the direction of gaze deviation. If looking to the intended path is the usual and most efficient strategy (Boer, 1996; Wann & Swapp, 2000), restraining gaze position to the TP, or even further inside the bend, could cause some perturbation. Finally, if any salient visual point along the road can be used to control the trajectory (Salvucci & Gray, 2004), no differences should be observed between experimental conditions.

**Methods**

### Participants

Four female and 9 male drivers, between 20 and 57 years of age (mean age of 26 years), participated in the experiment. They had been licensed drivers for 7.9 years and drove 12231 km a year, on average. In order to obtain a be experiments, drivers with astigmatism were not eligible to participate.

### Apparatus

The experiment was conducted using the fixed-base SIM² simulator developed by the MSIS laboratory (INRETS; for a detailed description, see Espié, Mohellebi, & Kheddar, 2003), which included an adjustable seat (no windshield), a steering wheel with force feedback, a gear lever, clutch, accelerator and brake pedals, and a speedometer. The vehicle model consists of two uncoupled algorithms to compute the motion of the car in the horizontal plane. The first algorithm determines the longitudinal behavior (speed and acceleration) of the car as a function of the current engine torque and brake friction. The second algorithm calculates the yaw motion as a function of the steering wheel angle and tire slip (Pacejka approximation and uniform adhesion coefficient). The vehicle is regarded as symmetrical and the direction is rigid. Sound effects include engine and gear changes noises.

The visual environment was retroprojected on a large translucent screen, viewed from a distance of about 2 m. The visual angle of the stimulus was about 62 × 51 degrees. The graphic database reproduced a real test track, situated in Satory (France), represented in Figure 2. The track was 3.4 km long. It consisted of 4 straight lines and 14 bends, 10 turning to the left and 4 turning to the right (total distance = 1940 m; mean radius = 221.1 m). The
driving lane was 3.3 m wide and delineated with a broken centerline and a continuous edge line. The simulated track was closely matched to the real one (same bend curvature, similar buildings, and surrounding vegetation), although the camber of the road was not reproduced. Details on each bend are given in Table 1. The mean lateral position corresponds to the deviation from the centerline in the direction of the inside edge line that was observed in the control condition. The mean distance of the TP was computed as a function of the mean radius of the bend and the mean lateral position of the car.

The driver’s gaze was monitored throughout the experiment by means of the IviewX gaze-tracker (Sensomotoric Instruments). The gaze-tracker was not coupled with a head-tracking device. Consequently, earth-based coordinates could not be computed. The gaze-tracker only provided head-centered videos, which allowed the driver’s gaze to be monitored throughout the experiment and recorded for later inspection.

### Procedure

After settling themselves in the simulator, the participants were given some preliminary instructions. Notably, they were asked to adopt a safe and reasonable speed and to keep in their lane without cutting the bends to the point of crossing the edge lines, even though there was no oncoming traffic. They were then invited to start the simulator and drive twice round the whole track for training purposes.

The twelve trials consisted of 6 experimental conditions, repeated twice. Two blocks of trials were performed one after the other, with the order of presentation of the 6 experimental conditions randomized inside each block for every participant. The 6 experimental conditions consisted of 1 control condition and 5 test trials. In the control condition, the participants were allowed to sample the visual scene as they wished. In the test trials, they were required to keep looking at a fixation point in the form of a small blue bar (Figure 3, right) to ensure a consistent position of gaze with respect to the lane. The position of the fixation point was always determined in relation to the position of the TP; that is to say as a function of the road geometry and the car’s position in the lane. The tighter the curve ahead, the greater was the angular deviation from the direction of heading and the smaller the distance from the car. As long as there is a bend ahead, it is always possible to calculate a TP. However, no fixation point was displayed in straight lines when the TP was more than 50 m away (light gray sections of the track on Figure 2). When approaching a bend, the TP indicated the entry point of the bend. When the car was close to the start of the curve and during the rest of bend negotiation, the TP moved along the inside edge line as a function of the evolution of the road ahead. For instance, the angle to the TP increased and its distance from the car decreased in entrance clothoids. Conversely, the angle to the TP decreased and its distance from the car increased in exit clothoids, up to its disappearance if the next bend was more than 50 m ahead. That way, no abrupt transition of gaze position was imposed on the driver. The only exception was when two bends, which followed different directions, came one after the other. In that case, the

<table>
<thead>
<tr>
<th>Bend number</th>
<th>Direction</th>
<th>Length (m)</th>
<th>Mean radius (m)</th>
<th>Mean lateral position (cm)</th>
<th>Mean distance of the TP (m)</th>
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<tr>
<td>B1</td>
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<td>170</td>
<td>124</td>
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<td>18.8</td>
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<tr>
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<td>170</td>
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<td>13.3</td>
<td>16.4</td>
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<tr>
<td>B3</td>
<td>L</td>
<td>170</td>
<td>55</td>
<td>14.7</td>
<td>12.9</td>
</tr>
<tr>
<td>B4</td>
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<td>230</td>
<td>79</td>
<td>52.2</td>
<td>13.4</td>
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<tr>
<td>B5</td>
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<td>140</td>
<td>500</td>
<td>25.1</td>
<td>37.4</td>
</tr>
<tr>
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<td>440</td>
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<td>35.0</td>
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<tr>
<td>B7</td>
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<td>130</td>
<td>231</td>
<td>18.2</td>
<td>26.1</td>
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<tr>
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<td>32.4</td>
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<tr>
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<td>100</td>
<td>28.0</td>
<td>16.6</td>
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<td>31.3</td>
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<tr>
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<td>38.4</td>
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<td>14.2</td>
<td>34.8</td>
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<tr>
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<td></td>
<td>138.6</td>
<td>221.1</td>
<td>23.7</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Table 1. Direction (L: Left, R: Right), length (m), mean radius of curvature (m), mean lateral deviation of the car from the centerline (cm), and mean distance of the TP (m) for all bends.
fixation point shifted from one lane marker to another at the time when the curvature of the road reversed. The position of the target differed across the 5 test conditions. It was positioned on the TP or at the same distance from the car but with a lateral offset of 82.5 or 165 cm along the line perpendicular to the direction of the TP, either inside or outside of the driving lane (Figure 3). Hence, when driving into a left bend, the target positioned at 165 cm to the right of the TP indicated the center of the driving lane. The target at 82.5 cm to the right of the TP lay between the center of the driving lane and the TP (the outer point with reference to the center of the curve). Targets that were positioned to the left of the TP (inner and innermost points) indicated more or less eccentric positions along a curve of smaller radius than the inner lane edge. Hence, both targets moved into the opposite lane. The reverse is true for right bends, except that, in these, the inner and innermost targets (offset to the right of the TP, this time) lay off the road.

The lateral position, steering angle, and speed were recorded throughout the trials at 50 Hz. The gaze-tracker allowed us to ensure that participants continuously looked at the target when this was present. As a matter of fact, gaze shifts from the fixation point were seldom observed during the experiment. The recorded videos were inspected following the completion of the study in order to gain a better understanding of the spontaneous strategies that were adopted in the free-gaze condition. After the experiment, the participants were invited to comment on the experiment. In particular, they were asked to evaluate how difficult they found driving with eye movements restrained to the vicinity of the tangent point.

Data analysis

The track was divided into 18 sections (14 bends and 4 straight lines). Data obtained in straight lines were discarded. For all sections and all trials, the mean and standard deviation of lateral position and speed were computed. Data obtained for identical conditions in the two blocks of trials were averaged. For mean lateral positioning (the only signed numbers of this experiment), the sign of left bends data was changed, so that a positive value represented a lateral deviation toward the inside edge of the driving lane, irrespective of the bend direction. The differences between each test condition and the control condition were examined using paired bilateral t-tests. In order to evaluate the effect of the visual target position, the value of the control condition was subtracted from all test conditions. One-way repeated measures analyses of variance (ANOVA) with the distance of the fixation target from the TP as the independent variable were performed on the obtained data sets. Newman–Keuls tests were used for post hoc analyses. The total number of steering reversals in bends (i.e., the number of times the steering wheel rotation changed direction) was also calculated. A Friedman ANOVA was performed to test the effect of the fixation point position and sign tests were used for paired comparisons. Because a realistic track was used, each bend was a particular case with a specific
length and curvature profile (entrance and exit clothoids of various length and strength, with or without an intermediate section of constant curvature), which entails a specific dynamic of the tangent point, a specific speed, etc. Thus, all bends differed along several dimensions at the same time. However, in order to determine whether some particular characteristics of the bends influenced steering, correlations were computed between the bend radius and the bend length on the one hand, and the mean values of all steering indicators in the corresponding bend on the other hand.

A more detailed inspection of the trajectories revealed that the effect of gaze manipulation varied depending on circumstances. Figure 5 illustrates this point. The top graph represents lateral positioning of the car during a sharp left bend (section A in Figure 2). Drivers entered the bend nearly the same way in all conditions. Paths started to diverge later during curve negotiation. In a more gentle bend further down the track, the effect of gaze manipulation was observed at the bend entrance and remained nearly constant later on (B: middle graph). When drivers had to negotiate two rapidly succeeding curves, in the manner of a chicane (C: bottom graph), the influence of gaze position was mainly observed when entering the first curve. In all cases, it can be seen that the more the eyes were directed toward the inside of the bend, the closer the vehicle remained to the lane center.

The mean lateral position in each bend did not significantly correlate either with bend length (r(12) = 0.27) or with bend radius (r(12) = −0.18) in the control condition. Similarly, the magnitude of effects observed in the test conditions, whatever the position of the fixation point, were not significantly correlated to any of these characteristics of the bends in particular.

**Steering stability**

Figure 6 shows the difference between test conditions and the control condition in terms of standard deviations of lateral position and number of steering reversals. Paired t-tests revealed that the standard deviation of lateral position was significantly smaller in all test conditions, compared to the control condition (p < .05 in all cases). An ANOVA performed on the difference between the 5 test conditions and the control condition revealed a significant effect of target position (F(4, 48) = 7.58, p < .001). Post hoc tests confirmed that the effect of target fixation was significantly smaller in the lane center and outer point conditions when compared to the other three conditions, which did not differ from each other.

A Friedman ANOVA performed on the difference between the test conditions and the control condition failed to reveal a significant effect of target position (χ²(4) = 8.66, p = .07). Sign test showed that the effect in the innermost condition was significantly smaller than in the inner point and outer point conditions (p < .05). The correlations between the reduction of lateral variability and the reduction of the number of steering reversals were significant in all test conditions except the innermost point condition, compared to the control condition (p < .05 in all cases).

Figure 5. Lateral position of the car averaged across subjects. The x axis (null lateral deviation) corresponds to the lane center. A positive value represents a deviation to the right. (A) In a sharp bend. (B) In a gentle bend. (C) In a chicane. (cf. Figure 2).

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**Results**

**Mean lateral positioning**

Figure 4 represents the mean lateral position of the car relative to the center of the driving lane. In the control condition, participants significantly deviated by 23.7 cm from the center of the driving lane toward the inside edge line (t(12) = 7.18, p < .001). The mean lateral position did not differ from the control condition when a visual target lay on the lane center (t(12) = 0.49, ns) or on the outer point (t(12) = 0.64, ns). However, the distance to the lane center significantly decreased when the target was positioned on the TP (t(12) = 3.74, p < .005), on the inner point (t(12) = 4.45, p < .001) or on the innermost point (t(12) = 4.75, p < .001). An ANOVA performed on the difference between the 5 test conditions and the control condition revealed a significant effect of target position (F(4, 48) = 7.58, p < .001). Post hoc tests confirmed that the effect of target fixation was significantly smaller in the lane center and outer point conditions when compared to the other three conditions, which did not differ from each other.

Figure 4. Average lateral deviation of the car from the lane center. A positive value represents a deviation toward the inside edge line. Error bars represent SEM.
conditions (lane center: \( r(11) = 0.72, t(12) = 3.4, p < .01 \); outer point: \( r(11) = 0.61, t(12) = 2.56, p < .05 \); TP: \( r(11) = 0.79, t(12) = 4.23, p < .005 \); inner point: \( r(11) = 0.62, t(12) = 2.64, p < .05 \); innermost point: \( r(11) = 0.6, t(12) = 2.48, p < .05 \)).

The standard deviation of lateral position in each bend did not significantly correlate either with bend length (\( r(12) = 0.13 \)) or with bend radius (\( r(12) = -0.13 \)) in the control condition. The correlation between the number of steering reversal and bend radius showed a similar non-significant inverse relation (\( r(12) = -0.35 \)). The correlation with bend length was highly significant (\( r(12) = 0.93 \)), but this is a trivial result (the larger the window of observation, the larger the number of corrections on the steering wheel).

**Discussion**

The tangent point steering strategy has been described in details by Land and Lee (1994). Basically, gaze is directed in the direction of the inside edge of the road 1 to 2 s seconds before entering the bend and returns to it during bend negotiation. Although no quantitative analyses of gaze position was performed in the current study, a careful examination of the videos revealed that the tangent point was routinely fixated in the free-gaze condition, with a large inter-subject variability in how it was performed. Gaze was also often directed to other parts of the scene such as other parts of the roadway or the dashboard. Normally, drivers also frequently look sideways at traffic signs or oncoming vehicles. This was not the case here because there were none to look at. Still, the fixation point in the test trials considerably reduced the mobility of the eyes compared to spontaneous behavior. When asked how disturbing constrained gaze had been, most subjects reported they were at ease with this part of the task, although most indicated that they preferred to be left free to look where they wished. Only one subject expressed real discomfort that had lasted throughout the experiment. This particular driver’s steering behavior did not differ from that of the other participants. None of the participants thought that it was detrimental to the steering task. Actually, the drivers did not exhibit a more conservative driving style when gaze was constrained. This was evidenced by the fact that speed remained nearly the same as in the control condition (with no increase in safety margins). Moreover, no detrimental effects were observed on steering indicators. Thus, objective performance data generally matched subjective reports to support the idea that constraining gaze strategies did not impair driving skills. Although Marple-Horvat et al. (2005) and Wilkie and Wann (2003) reached the opposite conclusion, there is no real contradiction here. In their studies, the detrimental effects of gaze constraint were mainly observed when subjects were asked to look straight-ahead, thus severely impairing eye-steering coordination. By contrast, in our experiment, subjects were required to look at a target that moved along the road curvature. So, eye steering coordination was preserved. In a way, it could be said to be improved since participants tracked the road curvature continuously.

Wilkie and Wann (2003) also compared a free-gaze condition to one where the drivers were given a fixation point that moved along the centerline at a constant distance of 16 m from the car. There was no effect on the variability of steering. The results presented here show that the stability of control increased when the fixation point was positioned on the TP and also when a lateral offset was added. This observation confirms and expands on the conclusions of a previous experiment that showed that indicating the TP to the driver (without a specific
requirement to look at it) could reduce the variability of lateral positioning in some circumstances (Mestre, Mars, Durand, Vienne, & Espié, 2005). This suggests that the dynamic properties of the fixation point gave some additional information for the control of steering stability. More specifically, the fact that it moved closer to the vehicle when the bend sharpened and further along when the bend smoothed out may have been essential. However, the orientation of the TP proper and its specific geometrical relation to the road curvature (Land & Lee, 1994) do not seem to be a crucial parameter in that process. This result is consistent with the two-level control models according to which distant visual information determines anticipatory steering maneuvers and ensures smooth trajectories (Donges, 1978; Land & Horwood, 1995; Salvucci & Gray, 2004). In normal conditions, previewing the road curvature by tracking the tangent point or another relevant target is not a continuous process since drivers need to attend to other features in the visual scene. The results presented here suggest that giving more weight to this part of the driving task may enhance the processing of distant visual cues for steering control. The increase in steering stability was observed for all target positions, except perhaps for the most extreme condition, whereby the driver’s gaze deviates most from the future path (innermost condition).

The improvement of steering stability was observed both at the trajectory and steering action levels, as evidenced by the reduction of lateral position variability and number of steering reversals, respectively. The variability of lateral position is traditionally an indicator of steering errors. This is true when the task consists of staying close to the road center when driving in a straight line. In bends, drivers naturally cut corners, as was observed here. Hence, you might expect greater standard deviations of lateral position when adopting a racing line than when keeping the trajectory close to the road center. Thus, a greater variability of lateral positioning may represent a less stable control of the vehicle, but also the tendency of drivers to adopt a straighter, maybe more efficient, path. Participants of the present study showed a contralateral deviation of the trajectory when fixating a target. In some bends, the deviation was nearly constant throughout the curve; in others, the drivers appeared to cut corners less when gaze position was constrained. The question is then: what does the reduction of path variability represent? If the variability of lateral position was determined entirely by how much drivers cut curves, we should have observed a reduction of lateral variability which was proportional to the effect on the mean lateral position. This was not the case: all fixed-gaze conditions showed a significant decrease of lateral position variability. More importantly, the analysis of steering reversals showed a similar profile. This variable is also an indicator of steering stability, when evaluated at the level of the effector (the steering wheel), rather than at the level of the resulting path (McGeehe, Lee, Rizzo, Dawson, & Bateman, 2004). The very strong correlation between the reductions in lateral position variability and the number of steering reversals when the gaze was manipulated supports the idea that both indicators reflect the same phenomenon, i.e., an improvement in control stability due to the continuous tracking of the dynamic properties of the visual marker.

All fixation points helped the driver to improve the stability of steering control, but the examination of mean lateral positioning of the car showed a different pattern of results. When free sampling of the visual scene was allowed, the drivers clearly cut the bends, i.e., they adopted trajectories that deviated from the lane center in the direction of the inside edge line. This is a common observation. Drivers usually tend to cut bends in order to minimize lateral acceleration (Reymond et al., 2001). When required to look close to the future path, at the center of the driving lane or at an intermediate position between the lane center and the TP, drivers cut the bends in approximately the same manner as in the control condition. By contrast, the more the driver’s gaze was directed toward the inside of the bends, the less the corner was cut. This is a surprising result. If steering actually does follow the eyes (Land, 1998), one would expect a trajectory deviation in the direction of the driver’s gaze. Readinger, Chatziastros, Cunningham, Büllthoff, and Cutting (2002) previously observed such a positive proportional relationship in subjects driving down a straight road. Steering was biased in proportion to gaze eccentricity when gaze was diverted from the direction of heading by a secondary task. Here, in bends and without diverting subjects from the steering task, a deviation of gaze in one direction yielded a deviation of the trajectory in the opposite direction when compared to the free-gaze condition. In some cases, this deviation was observed early on in the bend and remained nearly constant during negotiation of the whole curve. In other cases, the effect was more pronounced when entering or exiting the bend. Two tentative explanations can be put forward for this phenomenon. The inverse effect of gaze orientation on lateral positioning may be the result of the competition between both control levels described by Donges (1978) and Salvucci and Gray (2004). Previewing the road by looking at the inside of the bend may have drawn the driver in that direction, but the control process in charge of the correction of lateral position errors may have overcompensated for this deviation. In other words, asking subjects to look away from their future path may have changed the equilibrium between the anticipatory and corrective control levels, moving towards a trajectory closer to the lane center. Another, maybe more plausible, explanation is that manipulating gaze orientation modified the retinal flow generated by motion. Looking at the inside of the bend may have given rise to the perception of oversteering; in consequence, drivers did not cut the bends as much as in the free-gaze condition. Although a more extensive analysis of the relationship between gaze
positioning relative to the tangent point and retinal flow would be needed to verify this hypothesis, it would support the idea that a driver should direct his eyes where he wishes to go. The advantage of this strategy for drivers is that, whenfixating on a target position that is not on their current path, the projected retinal flow along the future path is curved in the opposite direction to the steering error (Kim & Turvey, 1999; Wann & Swapp, 2000). In that view, eye movements are an integral part of the process of extracting locomotor cues from retinal flow; the recovery of direction of heading as a primary input for steering control is not necessary. Actually, Wilkie and Wann (2006) demonstrated that observers were more accurate at directing their gaze in the direction of their future path than in the direction of heading when travelling along a curved path.

Conclusion

This study confirms that tracking a visual point moving down the road is an effective strategy for drivers when negotiating bends. In natural conditions, the most salient and easy to track feature of the road edge is the TP. The present results suggest that the dynamic properties of the TP or any other point that moves along the road, more than the direction of the TP and its geometrical relation to the curvature of the road ahead, are essential for the control of steering stability. A simple proportional control strategy with the direction of the salient distant point as the primary input signal is sufficient to account for this observation (Salvucci & Gray, 2004). On the other hand, the fact that no change in mean lateral positioning was observed only when drivers looked inside the lane boundaries favors the idea that looking where you wish to go determines the trajectory profile (Boer, 1996; Wann & Land, 2000). During natural driving, the gaze may be intermittently directed to the TP and the road ahead as a way to determine the future path and keep steering smooth at the same time.

This work is an experimental contribution to the fundamental problem of visual control in steering. It may also be relevant for the design of visual driving assistance systems. Indeed, the next generation of head-up displays in cars will offer the opportunity for a driving aid that offers a wide field of view and enhances relevant features in the visual scene. This raises the question of which visual cues should be made available in such displays. This study suggests that indicating a point along the oncoming trajectory in the vicinity of the TP may be a simple and efficient way to make vehicle control easier. Future work will try to determine if drivers can spontaneously use such a visual enhancement to improve steering without requiring them to perform continuous tracking.

Acknowledgments

This study has been supported by the European Program PREVENT (SafeLane) and by the French Program, PREVENTOR (ANR/PREDIT). The author is grateful to Susan Watts for English-language proofreading, to Robert Boisiliveau and Pedro Kvieska for assistance in data analysis, to Daniel Mestre for comments on the manuscript, and to the members of the MSIS laboratory who developed the simulator.

Commercial relationships: none.
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