

Car drivers attend to different gaze targets when negotiating closed vs. open bends

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On winding roads, car drivers have to control speed and steering angle in order to keep the car in an optimal lane position. Among the strategies proposed for steering regulation are the use of the tangent point, a geometrical method, and gaze sampling, in which retinal flow lines obtained by tracking a spot on the future road need to be assessed. Previous studies used a variety of scenarios (real-road vs. simulator) and different road designs (closed vs. open bends, different curvatures) and found results speaking in favor of either strategy. Here, we investigate what effects the openness of the bend, i.e. the sight distance of the driver, has on the percentage with which drivers use the tangent point. Six drivers drove a test car repeatedly through a series of twelve bends on real roads while their eye-movements were recorded. Results show that the reliance on the tangent point is generally high and increases with the closedness (shorter sight distances) of the bend and higher curvature. In open bends they alternatively look far into the straight road segments adjacent to the bend, but do not use gaze sampling.

Keywords: motion-3D, eye movements, heading, navigation, space and scene perception

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Introduction

Negotiating cars through bends relies on a combination of speed, steering and position in the lane, with speed and steering being the controllable actions and the position on the lane the resultant variable. For the control of steering, two major currently discussed strategies are orientation to the tangent point and gaze sampling.

The tangent point method for negotiating bends relies on the simple geometrical fact that the bend radius (and hence the required steering angle) relates in a simple fashion to the visible angle between the momentary heading direction of the car and the tangent point (Land & Lee, 1994). The tangent point is the point of the inner lane marking (or the boundary between the asphalted road and the adjacent green) bearing the highest curvature in the 2D retinal image, or in other terms, the innermost point of this boundary (Figure 1A). Drivers can easily use this strategy by looking at the tangent point and inferring the to-be-adopted steering angle from the rotation angle of their gaze and head in an open-loop fashion. If the driver steers correctly, the tangent point will stay in its retinal position. Additionally, the driver may then further use the tangent point in the manner of a closed-loop controller. If he under or oversteers the car, the tangent point will

deviate from the fovea. The driver can then adjust the steering until the tangent point is again in the desired position relative to his gaze direction.

Driving by the tangent point has been observed from both normal and racing drivers in real-world scenarios by Land and Lee (1994), Land and Tatler (2001), Chattington, Wilson, Ashford, and Marple-Horvat (2007), as well as in simulated races (Wilson, Chattington, & Marple-Horvat, 2008). The tangent point has further been noted as one of three possible attractors ('far points') in a recent model of car driving (Salvucci & Gray, 2004).

The alternative gaze-sampling method relies on retinal flow information (Wann & Land, 2000; Wann & Swapp, 2000). As an observer moves through an environment of visual objects, the representation of these objects on the retina changes with the movement, resulting in the retinal flow. The exact flow of each object depends on a number of parameters like the momentary heading direction and speed of the driver (i.e. his car), the depth structure of the environment and whether objects are static or move themselves. Heading, depth structure and independently moving objects can be derived from the optic flow by computational algorithms (Lee, 1980; Longuet-Higgins & Prazdny, 1980; Pauwels & van Hulle, 2004) and by human observers (Lappe, Bremmer, & van den Berg, 1999; Rogers & Graham, 1979; Rushton, Bradshaw, & Warren,

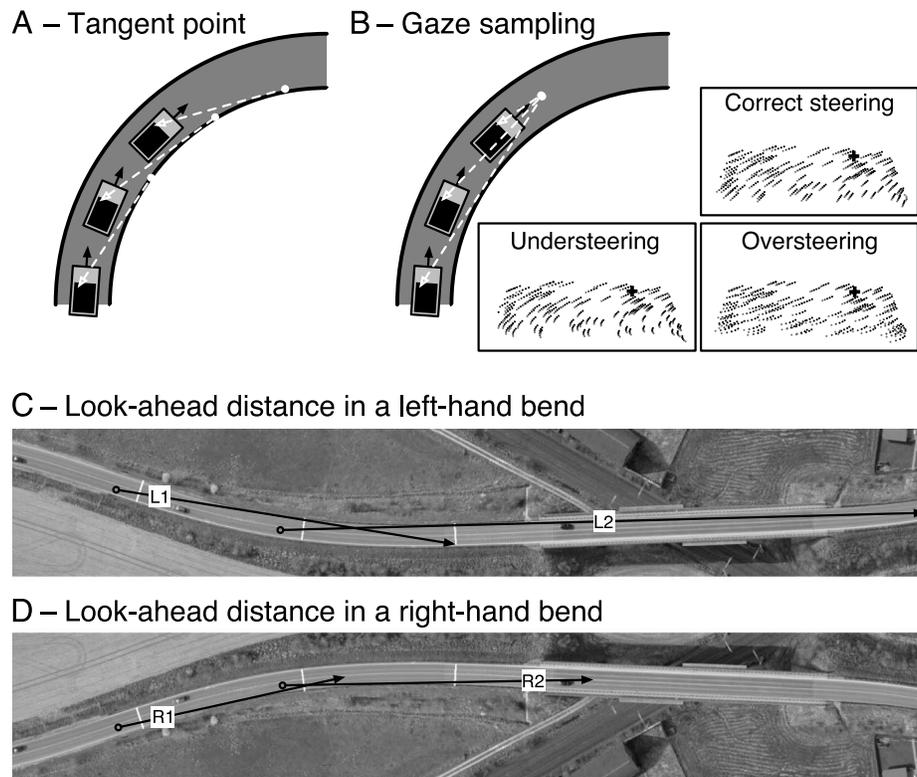


Figure 1. Two strategies for negotiating bends. (A) For driving by the tangent-point method, the driver fixates the tangent point as he drives around the bend. (B) For gaze-sampling, the driver fixates a point on the future track of the car on the street and keeps tracking it while he approaches it. Before crossing it, the driver looks out for a subsequent point to track. Insets show accumulated optic flow for understeering, correct steering and oversteering. Five consecutive positions are shown for each dot. Decreasing intensity refers to temporally older positions. (C) and (D) Sight distances in left and right-hand bends of one's own lane. The openness of a curve segment is defined by the sight distance at the point on the road at which drivers enter the segment. Entering segments of right-hand bends (R1) have a low degree of openness, leaving segments of right (R2) and entering segments of left-hand bends have a medium, and leaving segments of left-hand curves (L2) a high degree of openness. This is reflected by the sight distances in this example. R1: 87 m, R2: 123 m, L1: 118 m, L2: > 225 m. The photographs in C and D: (c) Google Earth, 2009.

2007; Warren & Hannon, 1988). Thus, from a combination of the momentary heading direction obtained from the flow and a high level representation of the street layout, it would be possible to decide whether one's car is on the track (Warren, 1998). But gaze sampling relies on much more basal information and thus avoids the more extensive computation of heading and scene structure as well as the balancing between them.

The cardinal idea in gaze sampling is that the observer's movement through the environment produces retinal flow lines and that these and especially their straightness or curvature can be determined by higher-order detectors (Wann & Land, 2000; Wann & Swapp, 2000; Wilkie & Wann, 2003b).

Using these flow lines for bend driving requires that the scene points before the driver lie in a plane, that observer first fixates a point on his intended path on that plane (cf. Figure 1B and insets), and then tracks that point for a short time interval. If he steers correctly, straight retinal flow lines will emerge. In contrast, if he understeers then

flow lines will be curved out of the bend (away from the fixation point), whereas flow lines curving into the bend will result if he oversteers (Wann & Land, 2000). Thus, the curvature of the flow lines provides a visual signal of steering correctness.

In order to use the gaze sampling method on winding roads, drivers have to fixate a spot on their future path (i.e. optimally in the middle of the lane) and track it for some time as they approach it. When it comes too near to the front end of their car to be comfortably fixated any further, drivers will look for a new point to track. For the periods of tracking the curvature of the flow lines has then to be assessed.

Wilkie and Wann (2003a) proposed that the visual system is able to distinguish between straight, left and right-curved flow lines and that observers are able to use the strength of the curvature to correct steering maneuvers accordingly. They placed subjects in a virtual environment and instructed them to negotiate a car through winding roads by using the gaze-sampling method. In that virtual

environment and with a moderate speed, subjects succeeded in driving that course safely (Robertshaw & Wilkie, 2008; Wilkie & Wann, 2003a).

In a study with real driving, we directly compared driving quality when using the gaze-sampling and when using the tangent point technique (Kandil, Rotter, & Lappe, 2009). We argued that flow lines obtained during driving on real streets are not as robust as in virtual reality because the car on the street, the driver in the car and the driver's head on his body are all moving irregularly due to the vibrations of the car and the unevenness of the street. Since these factors may well add substantial errors to the estimation of both position and vector of the motion information and may hence confound the mechanisms responsible for the distinction between straight and curved flow lines, we considered it worthwhile to investigate whether gaze sampling is used at all in successful bend negotiation, and if so with what precision. We conducted our experiment on the inner loops of cloverleaf motorway junctions, that is on fairly tight right-hand bends (radius of curvature ≈ 60 m).¹ These are closed bends, meaning that drivers can neither see their end point nor cut them short. We found that our subjects did not use gaze-sampling on their own and, if instructed to do so, drove less stably and not as smoothly as when using the tangent point. Our results thus contradict Robertshaw and Wilkie's (2008) results, who found that reliance on the tangent point was neither extensive nor significantly beneficial for the smoothness of the driving when they tested a similar strategy with subjects driving in a car-simulator.

It has been argued (Kandil et al., 2009; Robertshaw & Wilkie, 2008; Wilkie & Wann, 2003a) that next to the obvious difference of real-road vs. simulated driving, the parameters of the roads may play a role, that is whether the curvature is high or low and whether the bend is open or closed.

In the present study we take the idea of regarding open vs. closed bends and curvature a step further by defining openness as an entity. Imagine a driver approaching a curve. In order to negotiate the bend, he has primarily to steer the car according to the needs of the curve and to check the road surface for possible obstacles. Thus the most important part of the road is the section between his car and the point at which in his view the road surface of his own lane ends. (One may argue that he will be able to also see more distant parts of the road if he looks further off to the left or right. But in this case, he will lose sight contact to the primarily interesting gaze area. In correspondence with this view, we (Kandil et al., 2009) observed that these glances to the future path of the road are performed from time to time but that the driver's eye then quickly returns to the road section before him). We now define openness as the sight distance between the driver's eye and the subjective end point of his road lane. From geometrical considerations, it is clear that openness increases with increasing curve radius (i.e. with decreasing curvature). Further (as illustrated in Figures 1C and 1D) in

right-hand traffic, openness is larger in left than for right-hand curves (L1 and L2 are longer than R1 and R2) and for leaving as compared to entering sections (L2 and R2 are larger than L1 and R1) of otherwise identical roads. Additionally, it is striking that for the number of bends tested here, R2 is of approximately the same length as L1.

In this study, we test whether and to what extent openness predicts the driver's eye-related behavior. To this aim, we selected three test courses, each with a series of bends of differing curvature, and analyzed the eye-movements of a set of drivers separately for entering and leaving segments of left and right-hand bends of different curvature.

Material and methods

Location

Experiments took place on three defined country road courses near Lippstadt, Germany. As depicted in Figure 2, the three courses comprise bends of lower (especially course C1) and higher curvature (especially C3). Bends of modern roads consist of three segments: an initial segment with increasing curvature, an (often short) segment of constant curvature, and a final segment with decreasing curvature. While the short middle segment with the constant curvature can be fully described by its curve radius and length, the first and third section are built to the model of a clothoid (i.e. a cornu spiral), and can be characterized by the parameter A and the length. In these segments, the current radius (r) is a linear function of the path (x):

$$r = A^2/x. \quad (1)$$

Since the bends used here are built symmetrically and their middle segment is usually very short, we give here only the maximum radius and the total length of each curve (Table 1). We further split each into only two segments of equal length, which we will refer to as the "entering" vs. "leaving" segment, and which consists mainly of the clothoid parts.

Subjects

Six subjects, two females and four males, aged between 24 and 36 years, served as drivers in this study. While all of them were experienced drivers, five of them were naive as to the purpose of the study, while the sixth was the first author of the study. All of them had normal vision and none had experienced any major traffic accident during the five years before the experiments, nor any fear of driving a car in the test scenario.

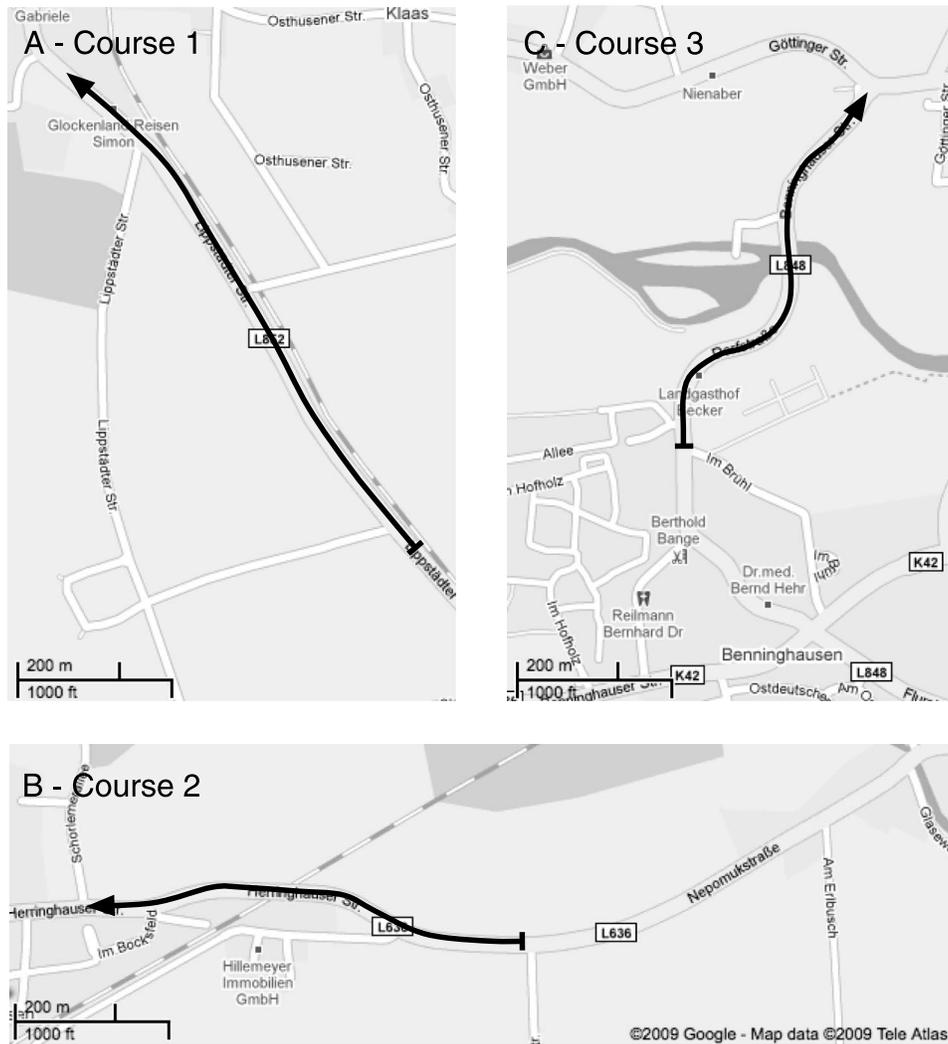


Figure 2. Layout of three courses. Bird's eye views of the three courses used in this study. The courses present the driver with individual bends of mainly low (A), medium (B) and high curvature (C). The photographs (c) Google Earth, 2009.

Bend	Total Length [m]	Steering Angle [°]	Direction	Sight Distance Entering [m]	Sight Distance Leaving [m]
C1.1	106	+17,3	right	67	54
C1.2	97	-7,5	left	105	290
C1.3	181	-2,5	left	>300	>300
C1.4	130	-6,0	left	>300	>300
C1.5	104	-10,1	left	80	110
C2.1	135	+15,9	right	87	123
C2.2	195	-14,9	left	118	250
C2.3	138	-14,2	left	118	250
C2.4	147	+15,8	right	87	123
C3.1	210	+33,6	right	54	69
C3.2	217	-33,1	left	73	81
C3.3	185	+33,2	right	64	80

Table 1. Total length (in meters), required steering wheel angle (in degrees), bend direction and sight distances in the entering and leaving segments (in meters) for the curves negotiated in the courses C1 to C3.

Street and action-related data

Subjects were seated in a test car, a Volkswagen Passat Variant (station-wagon) rebuilt for testing and research purposes. It is equipped with an additional electric power supply (1000 W, 230 V) that allows the operation of two full desktop computers with monitors and cameras attached. Via the CAN-bus,² system information about the driving parameters of the car, position on the street, GPS coordinates as well as information about the future course of the road, other cars and obstacles ahead are accessible. The car is equipped with an automated, video-based lane-detection system which among other parameters provides access to the current curvature of the road and to the applied steering wheel angle. Throughout this paper we will rather use the angle of the steering wheel since this is more intuitive than the road curvature, which is usually denoted in meters of curvature and which becomes infinite on straight road segments. However, the two parameters are indirectly proportional with the following formula:

$$\text{Steering Wheel Angle} = k/\text{Curve Radius}. \quad (2)$$

The constant parameter k depends mainly on the transmission ratio between the steering wheel and the tires and on the distance between the front and rear wheels of the car, but also on the transmission slip on that day and on the roads driven on. For our VW test car, k was empirically determined as being 3750 by registering both curve radius and steering wheel angle over the whole duration of the recording session and by computing the average ratio between them.

For the purposes of this study we recorded street-related parameters such as current distance from the left and right lane markings, current curvature of the lane, as well as action-related data such as current speed, acceleration, turning angle of the steering wheel and turning angle of the front wheels. Further we recorded 1.2 MB-images from a stereo camera set-up, placed between the inner rear mirror and the front screen. All data were sampled with a frequency of 20 Hz and saved along with the stereo camera images for off-line analysis.

Start and end points of the bends

Physical start and end points of the bends were determined on-site directly. We identified these points as the point, at which the road markings change from straight into curved. Although the beginning of the curve is built to the model of a clothoid, it can usually well be identified by a kink in the lane marking. Additionally, it is often accompanied by markings like station points, or fresh onsets of the asphalt.

The onset of the steering maneuver into a bend was identified as the point in time at which the steering wheel

was turned for the first time for more than 1 deg into the required direction.

Eye-tracking

After individual adjustment of mirrors and the seat, a light-weight head-mounted eye-tracker (Arrington Research, Inc., Scottsdale, AZ, USA), equipped with an additional 0.2 MB scene camera, was fixed on the subjects' head and calibrated. Scene-related eye-positions were stored along with the images from the head-mounted scene camera at a frequency of 30 Hz on the second computer. With this set-up mounted, subjects were free to look in all directions. No part of the visual field was occluded by the eye tracker. Data from the eye-tracker and the CAN-bus were synchronized by hand using the visibility of start and stop markers drawn onto the road surface before the actual tests began.

Tasks

Before the experiment subjects had a 10 minute period to get accustomed to the car and to driving with the equipment on. For the proper experiment, subjects drove five times on each of the three courses. As we were interested in the eye strategies they would normally engage to enter and leave bends of different curvature and direction, we instructed drivers to drive normally throughout the whole experiment, corresponding to the 'free' condition of our previous report (Kandil et al., 2009). Furthermore we arranged the starts of the individual trials in such a way that the course before the test car was free of cars. However, from time to time, a car would turn into our course from any of the side roads. Occasionally, our test car closed in on these cars. The concerned trials were excluded from further analysis and the trial was repeated. This way, some subjects drove up to seven times on the courses.

Data analysis

We use the gaze data obtained from the eye tracker to determine where, how often and how long subjects look at the different possible points on and around the future path during bend driving. To that end, we classified the gaze points by hand into one of 15 classes, among them the left, central and right lane markings; the tangent point where it appears on any of these lane markings; boundary posts to the left and right of the street; street signs and traffic lights; nearer (than 30 m) and farther aspects of the future road; as well as cars, pedestrians, bicycles and motor cycles on the same or opposite lane as the test car or on crossing roads. However, for the purpose of the analysis conducted here, classified data were subsumed into five

more general classes: (1) Lane Markings and Tangent Points (LM + TP), (2) Road, (3) Cars (as there were no pedestrians or other cycles in the streets on the recording days), (4) Signs and boundary posts, (5) Other.

We positively identified one of these as the attended target if the gaze was identified to lie within an area of 2 deg radius around its center. In cases, in which two targets were equally likely in single frames, we resolved the uncertainty by taking the frames before and thereafter into account.

We used then the CAN-bus steering and odometer signals as well as the GPS coordinates to first identify the curving stretches of the individual test tours, which we then further segmented into an “entering” and a “leaving” half. Additionally we labeled each stretch with the (maximum) radius and the orientation (left vs. right-bending) of the bend. We then analyzed whether the amount of time to which the drivers use the tangent point vs. gaze sampling strategy differs as a function of curvature, direction and bend segment.

Significance testing

In order to compare the percentages of time in which drivers used the tangent point, differences between conditions were tested using a repeated-measurement ANOVA. Individual conditions were additionally compared using Scheffé’s post-hoc test.

Results

We evaluated car-camera images, car-related data and gaze directions with respect to our central questions: Where do drivers generally look when they negotiate bends, i.e. which strategy do they employ for keeping the car on the lane? Do they employ different strategies for open vs. closed bends? We investigated this issue by analyzing whether drivers use different gaze targets in (i) left (open) vs. right (closed) bends, (ii) in entering (closed) vs. leaving (open) segments; and in bends of low (open) vs. high (closed) curvature.

Where do drivers look in general?

We recorded a total of 648 bends. In 15 of these, the gaze point could not be determined because during recording direct sunlight had interfered with the infrared eye-tracker too strongly. Another 68 bends had to be excluded as the driver had closed up too near to a slower car ahead and had from thereon relied on looking at that car (which, if the distance is kept constant, can serve as a marker for steering similar to the tangent point).

The remaining 565 bends were evaluated. Figure 3 shows that drivers use the tangent point about half of

the time ($59.3\% \pm 2.5$). This number is lower than the 75 percent we reported in our previous study (Kandil et al., 2009), where subjects drove on the cloverleaf lanes of a motorway junction. However, there we analyzed only the first two of three segments of the loops since we argued that in the third segment, subjects would have to look out for traffic (especially trucks) coming from the main motorway lanes into the exit lanes and would thus be distracted from orientating fully to the lane. As we show further below, the percentage is indeed higher for the first segments of the bend.

The second most frequent category of gaze directions is the road in front of the car ($29.9\% \pm 2.2$). These looks were mostly either long-lasting gazes to the end of the visible road or short glances to the road surface just in front of the car. These latter short glances occurred especially in the first tour of each driver. However, we did not find any series of glances to points on the road surface followed by continuous tracking of these points; the pattern subjects would have to show in order to use gaze-sampling as a strategy to negotiate bends.

The third category, cars, accounts for another 7.4% (± 0.3) of the gazes. These target cars were either further away on the same lane or driving in the opposite lane or any side road. Looks were rather short (500 ms) and were interleaved with orienting looks to the driver’s own lane. Note, however, that all those trials, in which the subject followed a car too closely, were excluded from analysis. Thus, in normal traffic, the proportion can be expected to be much higher. In the excluded trials, where subjects followed cars, the percentage of looks to the car ahead was as high as 72.1%.

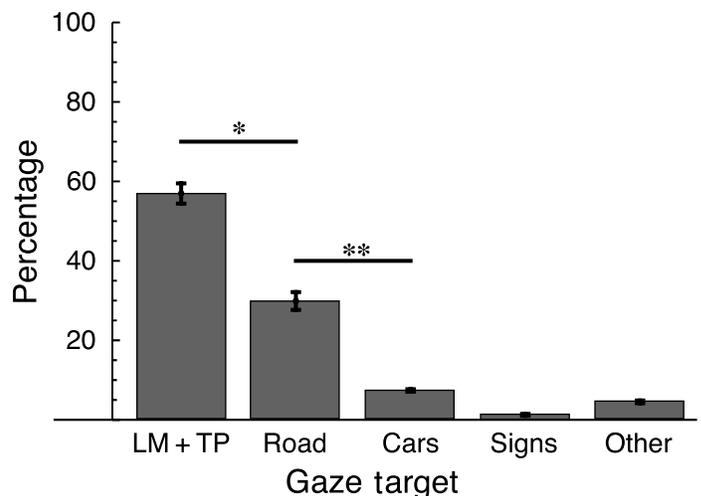


Figure 3. General results. Bars show the average percentage of the time the drivers spent looking at the tangent point and the lane markings just before the bends (LM + TP), the road surface (Road), cars, traffic signs, and other targets in the environment or within the car (radio, dashboard and the like). Bars show the average across six subjects ± 1 SEM.

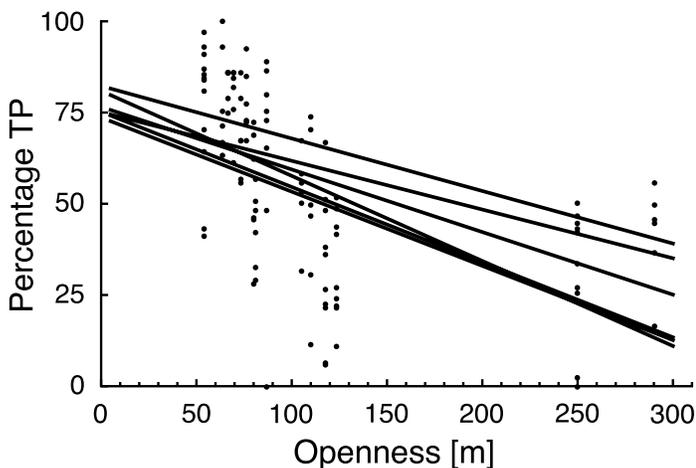


Figure 4. Dependence of the use of the tangent point on the openness. The graph shows, separately for each subject and openness of the individual bend, the mean (across $k = 5$ repetitions) reliance on the tangent point. The x and y-axis show the openness measured as sight distance (in meters) and the percentage of time spent on looking at the tangent point, respectively. The regression lines indicate linear models fitted to the individual data of single subjects. The average amount of explained variance is $r^2 = 0.278$.

The fourth category includes boundary posts and street signs. Subjects refer with brief looks to these signs in about 1.2% (± 0.2) of the time. Hence this category is rather negligible in relation to the residual category (“other”), which embraces looks into the landscape, to the sky, dashboard, radio, rear mirrors and the like, and accounts for up to $4.5\% \pm 0.3$ of the time.

Openness as a factor

As a prerequisite for the tests described below, we first controlled that openness really differs between the conditions tested here. As described above, openness was determined as sight-distances at the start point of the respective bend segment. It was measured using satellite views obtained from GoogleMaps (maps.google.com) and could be established for all twelve bends except the two shallowest ones. For the latter the sight distances would have been much greater than 300 m and were only constrained by the start of the next bends. As a result, we excluded these two bends from the analyses concerning openness (this section and Figure 4).

In respect to the first factor, bend direction, we found that in left-hand bends the mean openness was 147.1 ± 82.6 m (mean ± 1 SD), whereas it was only 80.8 ± 25.1 m in right-hand bends (Mann–Whitney-U-Test, ties-corrected $z = 2.229$, $p = 0.0129$). For the second factor, bend segment, we found that openness was indeed significantly shorter in entering vs. leaving segments (84.9 ± 22.5 m <

143.0 ± 86.7 m; Fisher’s exact randomization test for dependent samples: $z = 2.143$, $p = 0.0161$).

Figure 4 shows the use of the tangent point (in percent) depending on openness (in meters). Dots in the graph represent the relative use of the tangent point of one driver in one bend, averaged across the five times the driver negotiated this bend. Linear regression analysis was performed for each driver separately. The average amount of variance of the dependent variable that can be explained by the factor openness is 27.8%.

Dependence on bend direction and bend segment: Main effects

As mentioned above, if everything (especially road curvature) is held constant, left-hand bends can be considered more open than right-hand bends. We tested whether the reliance on the tangent point depends on the direction of the bend and found that this is actually the case (Figure 5A). The percentage of looks to tangent-point

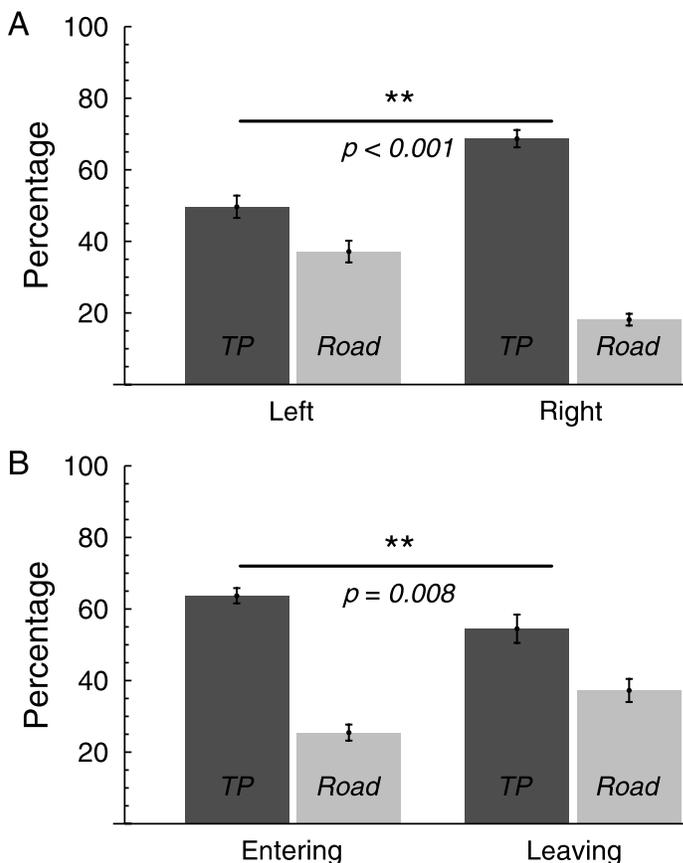


Figure 5. Main effects of bend direction and segment. Bars show the average percentage of the time the drivers spent looking at the tangent point and the lane markings just before the bends (TP), the road surface (Road), separately for left vs. right-hand bends (A), and entering vs. leaving segments of the bends (B). Bars show the average across six subjects ± 1 SEM.

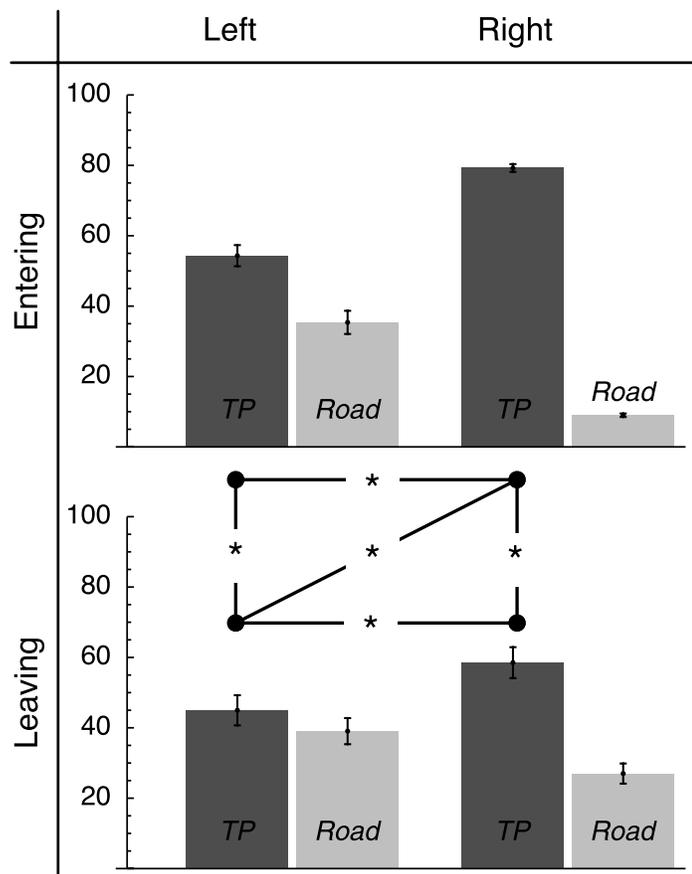


Figure 6. Interaction effects of bend direction and segment. Bars show the average percentage of the time the drivers spent looking at the tangent point and the lane markings just before the bends (TP), the road surface (Road), separately for entering segments of left and right bends, and leaving segments for left and right-handed bends. Bars show the average across six subjects ± 1 SEM. Lines with asterisks indicate significant differences between conditions, revealed by a Scheffé post-hoc test.

is significantly lower in left than in right-hand bends ($49.7\% \pm 3.1$ vs. $68.7\% \pm 2.4$, $F = 47.70 > F_{(1,5,0.99)}$, $p < 0.001$). This is a first evidence that the direction of the bend and thus its openness has indeed an effect of the reliance on the tangent point.

In a second step we investigated whether the ratio differs between the first and the second segment of the bends. As shown above, first (“entering”) segments are significantly more closed whereas second (“leaving”) segments are more open as the driver can again see more of the ending of the bend and of subsequent straight road segments. As the results in Figure 5B show, there is a significant difference between the entering and the leaving segment in respect to the proportion with which the tangent point vs. the road surface are attended. The percentage in the entering segment is significantly higher than in the leaving segment ($63.7\% \pm 2.1$ vs. $54.5\% \pm 4.0$, $F = 17.96 > F_{(1,5,0.99)}$, $p = 0.008$). Hence, also these results

favor the hypothesis that reliance on the tangent point depends on the openness of the bend.

Dependence on bend direction and bend segment: Interactions

In addition the interaction between bend segment and bend direction (Figure 6) was significant ($F = 7.64 > F_{(1,5,0.95)}$, $p = 0.039$). In order to consider this findings further, we conducted post-hoc comparisons between conditions using the Scheffé test ($D_{crit} = 7.49$). This analysis revealed that the reliance on the tangent point was significantly higher in the closed condition (entering right-hand bends: 79.3%) than in all other three conditions. Furthermore, the ratio in the two conditions with a medium degree of openness (leaving right and entering left-hand bends) did not differ significantly from each other (58.5% vs. 54.3%, respectively), but were both higher than in the most open-curved condition (leaving left-hand bends: 45.0%).

Dependence on the curvature

Finally we investigated the effect of curvature on the degree of reliance on the tangent point. To that end, we averaged individual data for each individual curve and performed a linear regression analysis across these data. Hence each dot in the graph of Figure 7 represents the mean across the 5 repetitions each subject performed on

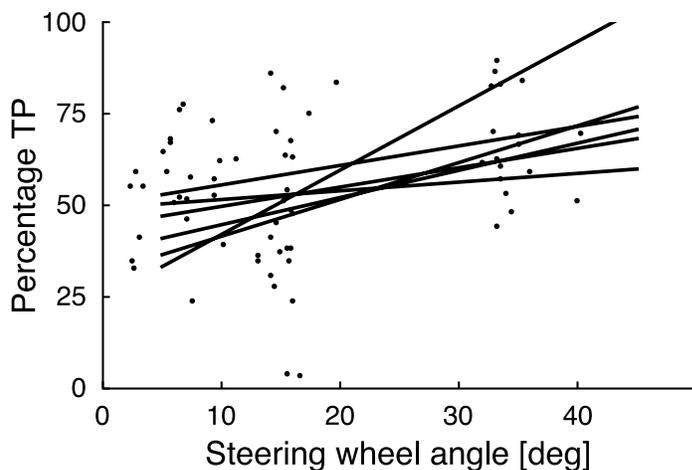


Figure 7. Dependence on the curvature. The graph shows, separately for each subject and individual bend, the mean (across $k = 5$ repetitions) reliance on the tangent point. The x and y-axis show the applied steering wheel angle (in degrees) and the percentage of time spent on looking at the tangent point, respectively. The regression lines indicate linear models fitted to the individual data of single subjects. The average amount of explained variance is $r^2 = 0.15$.

each of the curves. Curves range from around 3 to around 40 degrees of steering wheel angle, which corresponds to 1250 to 93.8 meters of curve radius, respectively. The figure shows a medium-range correlation between the curvature and the use of the tangent point. The average amount of variance explained by the individually fitted linear model is 15.0%. This seems to be reasonable given the large amounts of variance that have already been explained by curve direction and segment.

Temporal relation between eye movements and steering

The analyses described above show that the tangent point is the most often attended point during curve negotiation, but they also suggest that there are other targets drivers look at in order to steer a car through a bend. It may be that subjects principally use the tangent point in bends, but take the liberty to also look to the road if the situation is currently not serious; or that both road and tangent point are of general interest and drivers take turns in looking at either one. If the tangent point is principally important, then it should also be looked at especially just before the beginning of the bend, since the beginning of the bend is its most critical point. If a driver times his steering maneuvers adequately, then he can negotiate modern country road and motorway bends by (i) linearly increasing the steering angle, (ii) holding this steering angle and (iii) reducing it linearly again when leaving the bend. If, in contrast, the driver starts the initial steering maneuver too late then he needs to overcompensate the steering angle increase initially, which is then often to be followed by a series of steps of under and again over compensations in order get into the regular steering pattern again. As a consequence the start point of a bend can be considered its main critical point.

Thus in this final section we analyzed the eye movements just before and around the start point of the bend. We sought to investigate (i) how strong the use of the tangent point is at this critical point and (ii) whether the *time point* of the eye movement to the tangent point can be used to predict the exact *time point* of the steering maneuver, i.e. whether the temporal relation between the eye-movement and the car-directed action is coherent. To this end, we analyzed eye movements and steering actions in time intervals from 4 seconds before to 3 seconds after passing the physical start of the curve.³

We found that in 94.3% of the cases subjects looked at the tangent point before they started steering into the bend. This rate is much higher than the percentages obtained above, where we considered the gaze targets during the whole bend segment. This shows that the curve start is indeed a highly critical point and that the drivers use the tangent point here even more consistently in order to identify the curve start safely in space and time.

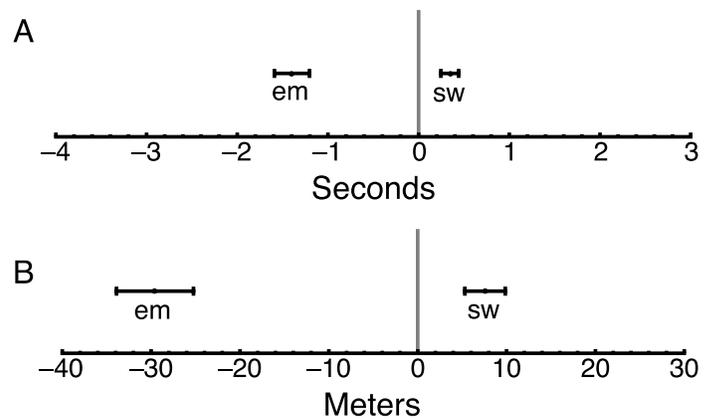


Figure 8. Timing aspects. Temporal relationship between the eye movement (“em”) to the tangent point, the physical starting point of the bend (vertical bar at the origin of the graphs), and begin of turning the steering wheel (“sw”). A and B show temporal offsets (in seconds) and spatial headway (in meters), respectively. They show a constant precedence of the eye movement over the steering wheel action taken by the drivers.

The second issue we aimed to investigate was the temporal relation between eye movement and steering maneuver. In about one third of the cases subjects had already started looking at the tangent point even before the analyzed time interval began, i.e. more four seconds before the bend start (and kept looking at it for the whole time interval of seven seconds). For these cases the temporal relationship could not be determined.

For 61% of cases, the time point of the first eye movement to the tangent point could be identified. For these cases, the average temporal advance to the start of the steering maneuver was 1.74 ± 0.22 seconds (see Figure 8A), corresponding to 37 m of way (Figure 8B).

In the remaining 5.6%, subjects did not attend the tangent point during the whole interval of interest. In all of these cases, drivers followed cars into left-hand bends, that is in situations for which the above findings (Figures 3 to 7) would predict the lowest engagement of the tangent point method.

Discussion

Effects of bend direction and segment

Our data show that drivers rely heavily on the tangent point. Subjects spent more than half of the time on looks at the tangent point. In contrast, we did not find any evidence for the use of the alternative gaze sampling method. No subject showed the eye movement pattern of looking at a certain spot on the future path of the lane and tracking this spot as it approaches. Instead, a third of the time is spent gazing at the end of the bend and into the

straight segments that follow the bend. The third largest target group was other cars.

We further found that there is a general tendency to make more use of the tangent point in right bound bends and entering segments of bends as opposed to left-hand bends and leaving segments. These effects sum up, so that the percentage of gazes to the tangent point is highest for entering segments of right-hand bends, which are by definition closed (blind-ended). At 80%, the figure resembles the values obtained in our previous study (Kandil et al., 2009). There, subjects kept driving in the loops of a motorway crossing, which consisted of right hand closed bends. This reliance on the tangent point is smaller for the other conditions. While for the leaving segments of right-hand bends as well as entering segments of left-hand bends the percentage sinks to an average of half of the time, it is still higher than the percentage of time they looked at the road. In the most open bend case, the leaving segment of left-turning bends, the tangent point and the bend's end are approximately equally attended. Taken together, what we found is an increase of the reliance on the tangent point from open to closed bends.

Effects of curvature

We also inspected whether driving strategy varies with curvature. Shallower bends are more open since the sight-distance of the driver is much longer. If the required steering angle is sufficiently small and the road sufficiently broad, he might even be able to look through the bend altogether right from the start of the bend. In contrast, stronger bends appear closed, as one can only see a few dozen meters ahead. In order to test for effects of curvature, we selected the three courses in such a way that they bear a variety of shallow, medium-curved and strong bends.

We found a medium-ranged correlation between curvature and percentage of tangent-point use. In fact, the curvature can explain 15% of the variance of the degree to which drivers use the tangent point. In the light of the very strong dependence of the use of this method on the question as to whether a bend leads to the right or left and whether the driver is in the entering or leaving section of the curve, the explained amount seems to be a reasonable contribution.

Openness as a factor

In total, the components determining the openness of the curve have all three proved in independent tests to be highly predictive of the degree to which subjects use the tangent point when negotiating curves. When openness was measured directly against the use of the tangent point, it explained more than a fourth of the total variance, i.e.

about twice as much as curvature. We thus conclude that openness itself is worth considering as a variable in future work.

Timing aspects

The temporal relationship between the direction of the gaze to the tangent point and the start of the steering wheel action revealed further that, in one of the more critical moments of bend negotiation, namely the start point of the bend, the reliance on the tangent point is very high with approximately 95% of the time looking at it. Land and Lee (1994) as well as Wilson et al. (2008) reported a strong coherence between eye-movements and steering actions and that the eye movements to the tangent point precede the car-directed action by a second. Here we find support for these numbers. In about two thirds of the cases, the temporal offset between eye and steering wheel action could be analyzed and lay at about 1.75 s within the same range as the reported figures, while in another third of the cases, the look to the tangent point occurred even more than 4 seconds before the curve start, indicating the importance for the driver to estimate the exact start point of the bend with high precision.

However, in a smaller fraction of the cases (5%), drivers did not look at the tangent point but rather on cars in front. While this can be considered an artifact of traffic volume, it has also been argued (Salvucci, Boer, & Liu, 2001) that the gaze angle to a car ahead followed with a constant distance, can also be used to infer the required steering angle, i.e. that a car driving ahead can be used much as the tangent point.

Eye-movement strategies

As an explanation for the differences between the four conditions (entering vs. leaving left vs. right-hand bends), we propose a model that takes the action the driver is about to take into account. In an adaptation and extension of Salvucci and Gray (2004), it states that the driver chooses *the* orientation point in the scenery before him that suits best the actions he intends to take. If he aims to go into the bend and to stay in his lane (small values of openness), he relies more on the tangent point. If he can cut the bend, that is if he may at least partially leave his lane, or when, after the apex of the bend, he is to straighten the car in the lane again (large values of openness), he relies more on looking at the end of the bend.

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Footnotes

¹The experiments were conducted in Germany, that is in a country that drives on the right. Note that in order to obtain similar results in countries with left-hand traffic like the UK, Japan and Australia, one would have to regard drives in the left-hand 270°-loops cloverleaf motorway junctions. However, in these countries junctions are more commonly built to the model of either a turbine or a maltese cross, where the indirect path has a much larger radius (flyover ramp).

²The CAN-bus (Controller Area Network) is a serial field bus system, developed in the 1980s in order to reduce the total length (and weight) of cables in the car. It connects the various controllers in the car by a single wire system and gathers and disseminates all the information from the controllers in a common ‘telegram’ which is periodically updated. We record and store the information from the CAN-bus along with the pictures taken by the two car cameras.

³The interval had to start 4 seconds (or 100 m) before the physical curve start as this was the minimum distance between two consecutive bends.

References

- Chattington, M., Wilson, M., Ashford, D., & Marple-Horvat, D. E. (2007). Eye-steering coordination in natural driving. *Experimental Brain Research*, *180*, 1–14. [PubMed]
- Kandil, F. I., Rotter, A., & Lappe, M. (2009). Driving is smoother and more stable when using the tangent point. *Journal of Vision*, *9*(1):11, 1–11, <http://journalofvision.org/9/1/11/>, doi:10.1167/9.1.11. [PubMed] [Article]
- Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*, 742–744. [PubMed]
- Land, M. F., & Tatler, B. W. (2001). Steering with the head: The visual strategy of a racing driver. *Current Biology*, *11*, 1215–1220. [PubMed]
- Lappe, M., Bremmer, F., & van den Berg, A. V. (1999). Perception of self-motion from visual flow. *Trends in Cognitive Sciences*, *3*, 329–326. [PubMed]
- Lee, D. N. (1980). The optic flow field: The foundation of vision. *Philosophical Transactions of the Royal Society of London B*, *290*, 169–179. [PubMed]
- Longuet-Higgins, H. C., & Prazdny, K. (1980). The interpretation of a moving retinal image. *Proceedings of the Royal Society of London B: Biological Science*, *208*, 385–397. [PubMed]
- Pauwels, K., & Van Hulle, M. M. (2004). Segmenting independently moving objects from egomotion flow fields. Early Cognitive Vision Workshop, Isle of Skye, May 28–June 1 2004.
- Robertshaw, K. D., & Wilkie, R. M. (2008). Does gaze influence steering around a bend? *Journal of Vision*, *8*(4):18, 1–13, <http://journalofvision.org/8/4/18/>, doi:10.1167/8.4.18. [PubMed] [Article]
- Rogers, B. J., & Graham, M. E. (1979). Motion parallax as an independent cue for depth perception. *Perception*, *8*, 125–134. [PubMed]
- Rushton, S. K., Bradshaw, M. F., & Warren, P. A. (2007). The pop out of scene-relative object movement against retinal motion due to self-movement. *Cognition*, *105*, 237–245. [PubMed]
- Salvucci, D. D., Boer, E. R., & Liu, A. (2001). Toward and integrated model of driver behavior in a cognitive architecture. *Transportation Research Record*, *1779*, 9–16.
- Salvucci, D. D., & Gray, R. (2004). A two-point visual control model of steering. *Perception*, *33*, 1233–1248. [PubMed]
- Wann, J., & Land, M. (2000). Steering with or without the flow: Is the retrieval of heading necessary? *Trends in Cognitive Sciences*, *4*, 319–324. [PubMed]
- Wann, J., & Swapp, D. K. (2000). Why you should look where you are going. *Nature Neuroscience*, *3*, 647–648. [PubMed]
- Warren, W. H. (1998). The state of flow. In T. Watanabe (Ed.), *High-level motion processing*. Cambridge: MIT-Press.
- Warren, W. H., & Hannon, D. J. (1988). Direction of self-motion is perceived from optical flow. *Nature*, *336*, 162–163.
- Wilkie, R. M., & Wann, J. P. (2003a). Controlling steering and judging heading: Retinal flow, visual direction, and extraretinal information. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 363–378. [PubMed]
- Wilkie, R. M., & Wann, J. P. (2003b). Eye-movements aid the control of locomotion. *Journal of Vision*, *3*(11):3, 677–684, <http://journalofvision.org/3/11/3/>, doi:10.1167/3.11.3. [PubMed] [Article]
- Wilson, M., Chattington, M., & Marple-Horvat, D. E. (2008). Eye movements drive steering: Reduced eye movement distribution impairs steering and driving performance. *Journal of Motor Behavior*, *40*, 190–202. [PubMed]