# Driving is smoother and more stable when using the tangent point

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Car drivers can employ a number of strategies to negotiate curves. The tangent point strategy proposes the use of the angle between the tangent point of the inner lane markings and the car's current heading direction, which is proportional to the required steering angle. The gaze-sampling strategy proposes to fixate points on the future path and measure the curvature of optic flow vectors which can inform the drivers whether they over- or under-steer. Nine subjects drove repeatedly on the four loops of a motorway junction for which street parameters were available, while eye-movements, steering parameters and relations of the car to the lane were recorded. In the first half of the trials, we observed which strategy drivers normally use, whereas in the second half, we instructed subjects to use exclusively either the tangent-point or the gaze-sampling strategy and observed their steering behavior. Our results confirm that subjects normally look at the tangent point whereas they do not use gaze sampling of their own accord. Further, subjects drive more smoothly in terms of position on the lane and steering stability in the tangent-point condition.

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

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## Introduction

Driving a car successfully through a curve requires 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, the two major strategies currently discussed are gaze sampling and orientation to the tangent point.

Gaze sampling is a method relying 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 (independently). 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, 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 optic flow lines and that these flow lines and especially their straightness or curvature can be determined by higher-order detectors (Wann & Land, 2000; Wann & Swapp, 2000; Wilkie & Wann, 2003b). Optic flow lines emerge from the flow by tracing the positions and direction vectors of significant points over time. The easiest case of driving straight ahead on a straight street with the gaze focussed on the vanishing point of the street (focus of expansion) will for example produce straight lines. In contrast, if the observer focuses e.g. the ground near a reflector post to the right of the lane, flow lines with be bent to the left, that is curved away from that point of fixation.

Using these flow lines for curve driving requires that the scene points before the driver lie in a plane and that observers fixate a point on their intended path on that plane (cf. Figure 1 and insets). If they then steer correctly, straight retinal flow lines emerge. In contrast, if they understeer then flow lines will be curved out of the curve

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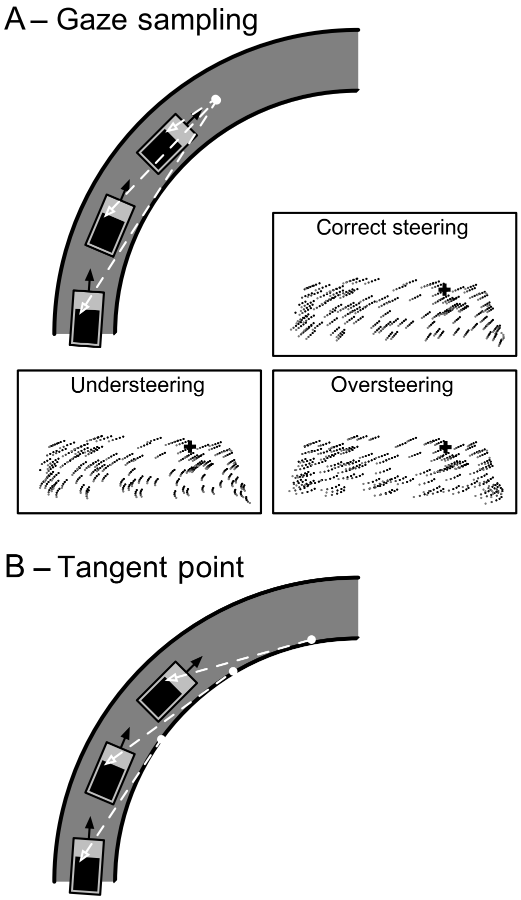

Figure 1. Two strategies for negotiating curves. (A) For gaze sampling, the driver fixates a point on the future track of the car on the street and keeps tracking it while he approaches it. Before crossing it, the driver looks out for a subsequent point to track. Insets show accumulated optic flow for understeering, correct steering and oversteering. Five consecutive positions are shown for each dot. Decreasing intensity refers to temporally older positions. (B) For driving by the tangent-point method, the driver fixates the tangent point as he drives around the bend.

(away from the fixation point), and if they oversteer than flow lines bending into the curve will result (Wann & Land, 2000). In order to use the gaze sampling method in a curvy environment, drivers have to fixate a spot on their future path 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 (Figure 1A). 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 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 curvy streets 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).

However, gaze sampling has never been tested in settings other than these artificial ones. One could argue 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 wobbling due to the vibrations of the car and the unevenness of the street. 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. Hence one of the aims of this study is to investigate whether gaze sampling is used at all in successful curve driving, and if so with what precision.

The alternative tangent point method for negotiating curves does not rely on optic or retinal flow but rather simply on the estimation of the angle between the tangent point and the momentary heading direction of the car. Drivers can easily use this strategy by looking at the tangent point and by detecting deviations of its retinal location (Land & Lee, 1994; Land, 1998). The tangent point is the point of this inner lane boundary bearing the highest curvature in the 2D retinal image, or, in other terms, the innermost point of this line. For this method either the lane marking of the street or the boundary between the asphalted way and the adjacent green can be used. The critical task for the driver is to fixate the tangent point and estimate the angle between momentary heading direction of the car and the tangent point (Figure 1B). The driver has then to turn the steering wheel to an extent that depends linearly only on that tangent-point angle and on the lateral distance from the car to the lane marking. As soon as he has then found and set the adequate steering angle, he has to monitor whether the tangent point stays in the desired position on his retina (namely the fovea). If he over or understeers the tangent point will move out of the fovea, a deviation compensated by adequate eye movements. In the manner of a closed-loop controller, 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) and Land and Tatler (2001).

Here for the first time we put both methods to the test against each other on real roads. We chose to have drivers go round the inner four loops of cloverleaf motor way junctions as for these the street parameters were available to us. This allows us to test driving under gaze sampling and tangent point conditions independently against the ideal following of the curve, and see under which conditions subjects drive better in terms of steering stability. Our results favor the tangent point condition.

# Materials and methods

## Location

Experiments took place on two motorway junctions in Germany, namely the crossings Werl and Erwitte/Anröchte, situated along the autobahn A44. As depicted in Figure 2A, German motorway junctions are typically cloverleaf interchanges, in which right-turning traffic is handled by a direct ramp before the actual junction, whereas left-turning traffic is handled by an indirect ramp behind the junction, i.e. a 270 degree right-turning loop.

The course used for this experiment consisted of the four inner loops and the straight collector/distributor roads between them. Modern loops (like the ones we used) comprise three sections: turning into the curve, constant turning and turning out of the curve (Figure 2B). While the middle section with the constant curvature can be fully described by the curve radius and its length, the first and the third section are characterized by the parameter A and the length of a clothoide (i.e. a cornu spiral), where the radius ($r$) is a linear function of the path ($x$):

$$r = A^2/x \tag{1}$$

As a result the steering angle of an ideally driven car in such a loop first increases linearly, then stays constant and finally decreases linearly again. Table 1 denotes the parameters for the four loops of the two junctions.

A – Motorway junction

B – Sections of a single loop

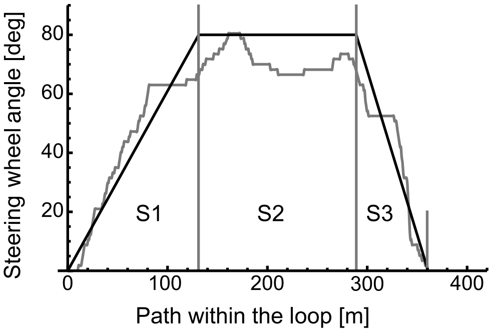

Figure 2. Layout of the course. (A) Cloverleaf motorway junction with the test course consisting of the four loops. (B) Each loop is sub-divided into three sections separated here by vertical gray lines: Turning into the curve (S1), constant curvature (S2) and turning out of the curve (S3). The steering angle increases linearly, stays constant and falls linearly again to zero in the sections, respectively. For demonstration, empirical steering data for a random trial on that loop (driver FK) is additionally shown (gray line). The photograph (c) Google Earth, 2008.

| | Segment 1 | | Segment 2 | | Segment 3 | |
|---|---|---|---|---|---|---|
| | A [m] | L [m] | R [m] | L [m] | A [m] | L [m] |
| Werl | | | | | | |
| 1. SE | 81.0 | 130.0 | 50.0 | 145.3 | 70.0 | 97.2 |
| 2. SW | 81.0 | 131.0 | 50.0 | 143.4 | 70.0 | 98.0 |
| 3. NW | 88.0 | 110.2 | 70.0 | 261.6 | 70.0 | 70.0 |
| 4. NE | 85.0 | 111.7 | 65.0 | 231.2 | 70.0 | 75.3 |
| Erwitte | | | | | | |
| 1. SE | 86.0 | 114.6 | 65.0 | 241.0 | 69.0 | 71.0 |
| 2. SW | 83.0 | 105.2 | 65.0 | 252.0 | 65.0 | 66.0 |
| 3. NW | 81.0 | 131.0 | 50.0 | 158.0 | 60.0 | 71.0 |
| 4. NE | 75.0 | 111.7 | 50.0 | 138.4 | 70.0 | 97.8 |

Table 1. Clothoide (A) or radius (R) and length (L) for the three segments of the four loops (southeast, southwest, northwest, and northeast) for the two motorway crossings (Werl and Erwitte).

## Subjects

Nine subjects, three females and six males, all aged between 28 and 39 years, served as drivers in this study. While all of them were experienced drivers, seven of them were naive as to the purpose of the study. All of them had normal vision and none had experienced any major traffic accidents during the five years before the experiment. Further, none of them had any fear of driving a car in that scenario.

## 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, 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 provides access to the distance of the car to the left and right lane markings and the current curvature of the road.

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 inner rear mirror and front screen. All data were sampled with a frequency of 20 Hz and saved along with the stereo camera images for off-line analysis.

## 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.

## 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 48 to 60 loops, corresponding to 12 to 15 full cloverleaves.

The first 24 to 32 loops were reserved for the "free-driving" condition (abbr. "free"), in which we instructed subjects to "just drive" through the junction. Then, subjects were instructed to negotiate the loops by looking permanently at the tangent point (abbr. "tang") for the next 12–16 loops, while the last 12–16 ones were reserved for the gaze-sampling method ("gaze"), for which subjects were asked to successively look for and keep fixating for several seconds at points on the future path of the car. For some subjects, the order of "gaze" and "tang" trials was reversed. Occasionally, other cars and vans changed over from the main motorway lanes to the collector/distributor lane in order to take the same loop as the subjects. If these cars were close enough and slow enough to be followed, then the condition for this single loop was changed to "car ahead" (abbr. "car"). There, the first six subjects were instructed to fixate permanently on the number plate of the car ahead, whereas the last three drivers were told that this trial would go uncounted and that they could behave normally. In either case, the trial was repeated at the end of the experiment with the condition originally intended for it. Analysis of driving parameters below was restricted to the trials of the first six subjects.[1]

## Data analysis: Car data

In a preparatory step, the radius, clothoide and length parameters were assembled to a model of how to ideally negotiate the four loops of each junction separately.

Then, individual driving data were analyzed. Using the video images from the car stereo cameras, the precise start and end point of each loop was identified manually with an uncertainty of ±25 ms (corresponding to the 20 Hz temporal resolution of the cameras). According to these points, the data stream was broken down into individual trial streams, each starting 1 s (approximately 15 m) before and ending 1 s (approximately 15 m) after the corresponding points.

In a second step, we computed the distance covered from the momentary velocity data obtained for each time point. As a check, the totally covered distance in a loop was cross-checked against the lane length given by the model. The error was below 2%.

In a third step then, these trial streams were sub-divided into the three previously mentioned sections (turning into the curve, constant curvature and turning out of the curve), according to the ideal model of the street. For each trial and section, the constant and the variable errors were then computed, i.e. the reciprocals of the accuracy and the precision, respectively. This was done for the distance to the right lane markings (abbr. "distr") and the angle of the steering ("steer").

Fourth, for all three variables and the three sections, we computed means and variances separately for the four conditions. This allowed us to compare the smoothness of driving between the driving conditions.

## Steering into the loops

Of particular interest was the point in space at which subjects drove into the curve in the different conditions. Therefore, we determined for each trial separately the point in space at which the steering wheel was turned for more than 1 degree. Averages were compared across conditions.

## Data analysis: Eye data

Here, we use the gaze data obtained from the eye tracker to determine where, how often and how long uninstructed subjects look at the different possible points on and around the future path during curve driving. Therefore we classified the gaze points by hand into these six classes: tangent point, left and right lane markings, points on the road surface (future path), traffic, rest (looks on points inside the car or anywhere else except the road).

# Results

We evaluated recorded car-camera images, car-related data and gaze directions with respect to two questions: First, where do drivers normally look when they go into and drive through curves, i.e. which strategy do they employ for keeping the car on the lane? Second, how well in terms of stability of steering and distance to the inner lane marking do subjects drive when they are instructed to use exclusively either the tangent-point or the gaze-sampling method? Finally, we compare the data to decide which strategy drivers use when uninstructed.

## Where do drivers normally look?

The first 24 to 32 loops were dedicated to the uninstructed ("free") driving condition. For these loops, we manually classified the points in the outside world the drivers normally look at while negotiating curves. We defined six possible categories, (1) the tangent point, (2) the left lane-marking, (3) the right lane marking closer than the tangent point, (4) the street ahead, (5) the car ahead, where applicable; while the landscape as well as the interior of the car served as residual categories (6).

As shown in Figure 3, subjects normally look at the tangent point on average for about three quarters of the time, at the street ahead for about 14%, and at the right lane marking for about 6.5%. Left lane marking and landscape seem to be negligible points with less that 3% each. If a car is driving ahead, then drivers who are left uninstructed for this case (i.e. the last three drivers) seem to check its distance with occasional short glances (5.5%) only but otherwise neglect it.

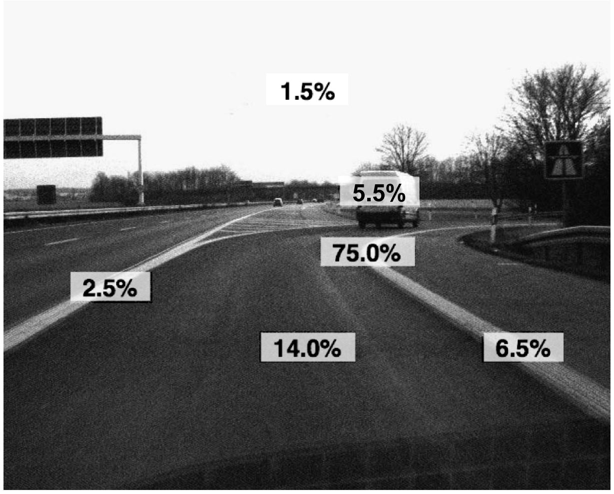

Figure 3. Fixation targets during curve negotiation. Percentage of the total time spent by the subjects looking at the left and right lane marking, the middle of the street, the tangent point (75%), cars ahead as well as the environment. Note that the percentage spent for looking at cars ahead is computed only in relation for the trials with a car directly in front of the test car.

Although our data show that subjects look at the street ahead, their vertical viewing angle remains constant during these periods. Hence, our data indicate that they do not follow any fixated spot on the ground and do not spontaneously use gaze sampling in order to stabilize the course of the car. Rather it seems that they simply stare onto the street before them.

In a second step we looked for any evolution of these patterns over time, that is across these first loops. We found that in the beginning overt attention as expressed by the eye glances is shared equally between tangent point and the street. As drivers get more accustomed to the road (loops), they also concentrate more on the tangent point and seem to neglect the street itself, so that in the last quarter of loops, only 4% of the time is spent looking at the lane whereas in some 85% of the time the driver orients to the tangent point.

A third aspect was the first point in time at which drivers look at the tangent point during the seconds before entering the curve. Land and Lee (1994) had reported that the first glance to it occurs some 2 to 3 seconds before drivers turn the steering wheel. However, we found here that during these three seconds before they start into the curve, drivers look at the straight segment of the lane marking just ahead of the car at an angle of about 30 to 45 degrees right from the heading of the car and that they look directly at the tangent point only approximately 150 ms before steering into the curve.

## Starting into the curve

Of particular interest are the first moments of turning into the curve. In order for drivers to go into curves in a smooth way, they should wait until the starting point of the curve and then turn the steering wheel according to the momentary curvature of the street.

Our data demonstrate that this is exactly the case for the trials in the tangent-point condition. Figure 4A shows the gradual increase of the steering angle for the first twenty meters of the curve, separately for the four driving conditions and averaged across all subjects. The black trajectory marks the course for the tangent-point condition. There, drivers go into the curve very early and keep an almost parallel course in relation to the parameters of the street (diagonal dashed line). In contrast, trajectories in all other conditions start later into the curve, but increase steering angles more rapidly, so that after some ten meters the steering angle is higher than in the tangent-point trials.

To analyze this matter more quantitatively, we determined starting points individually for each trial and then calculated means and standard errors across subjects. On average (Figure 4B) subjects showed a tendency to start earlier into the curve when they

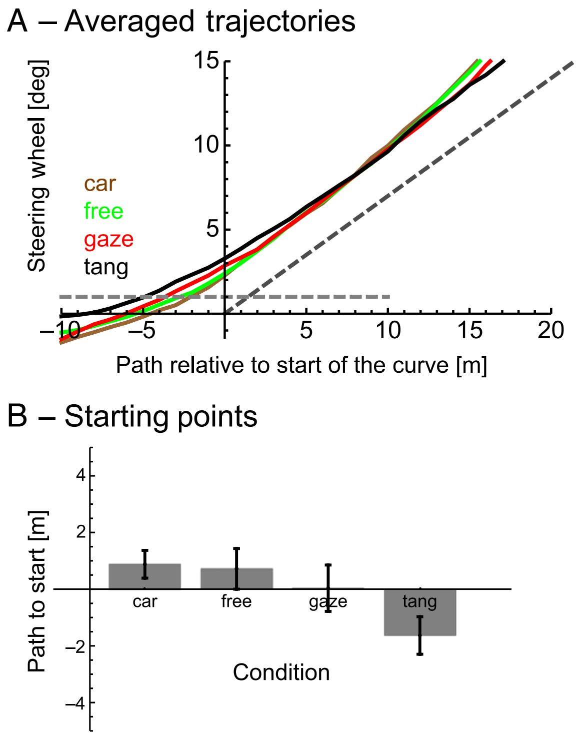

Figure 4. Starting into the curve. (A) Trajectories averaged separately for the four conditions (car, free, gaze, and tang) across the four subjects. The horizontal dashed line corresponds to a steering wheel angle of 1 deg and served as a threshold indicating the start of steering action. The diagonal dashed line marks the set point given by the street. (B) Relative start points (means ± 1 *SEM*) for the four conditions. In order to correct for individual tendencies to enter curves early or late, individual absolute start points were averaged per subject and then corrected for the mean across all conditions, before averaging them across subjects.

employed the tangent-point as compared to the gaze-sampling ("gaze") or uninstructed ("free") condition (Randomization test for three dependent samples, corrected $p = 0.10$) by approximately 2 meters.

## Stability of driving in instructed conditions

A driver totally complying with the model of the street would drive straight until the loop begins, then turn the steering wheel linearly according to the parameters of the loop, then hold the steering angle and then diminish the steering angle again linearly[2]. This should then give a maximally smooth drive. To quantify the smoothness of the drive, we computed constant errors (= 1 / precision) and variable errors (= 1 / accuracy) for steering angle and distance from the right lane markings for the first and second segment of the loops. We neglected the third segment altogether assuming that there the attention always needs to be divided between the task of steering and the observation of the future traffic coming onto the exit lane. Furthermore, in this last segment, the task is normally to redirect the car again into the middle of the lane, making the value of a putative full alignment with the tangent point questionable.

A first glance on the data for steering (Figure 5A) and distance to the right lane markings (Figure 5B) reveals that all errors in all variables and in all sections are roughly comparable to one another, independent from the experimental condition. This may seem as if **eye-movement** strategy does not make much of a difference. However, given that the lane was defined and that no subject caused any accident, one must expect that subjects steered the car according to the requirements of the lane and thus reasonably accurate. Thus one cannot expect too strong deviations from the ideal here and must attach importance to fine differences.

First, we concentrated on the steering angle (Figure 5A). The two left panels show the constant and the variable error for the first section of going into the curve. It appears that subjects constantly oversteer by 2 to 4 degrees, that is they anticipate the curvature demanded approximately 0.2 to 0.4 seconds ahead or 3 to 6 meters of distance, which roughly corresponds to the distance between the car's front and the spot of the street fixated by the driver. Oversteering seems maximal in the tangent point condition; however, the difference is statistically insignificant (Randomization test, $Z = 1.06$, $p = 0.856$) and may result from the first few meters of the loop where drivers start much earlier into the curve in the tangent point condition (see above). In contrast the variable error is lower in that condition than in all the other conditions (Randomization test, $Z = -2.28$, $p = 0.011$), indicating that driving was smoother there.

Turning to the second section of the loop with constant curve parameters (right panels in Figure 5A), the errors change from over to understeering, which partly arises in order to compensate for the constant oversteering during the first section and partly reflects the logic of driving maneuvers: a short stretch of oversteering must be compensated by a much larger stretch of understeering. Thus, even an average understeering of roughly 8 degrees (approximately 10%) can result. However, as can be seen, when drivers oriented themselves using the tangent point the constant error was lowest (Randomization test, $Z = -1.97$, $p = 0.024$) and so was the variable error (Randomization test, $Z = -1.89$, $p = 0.029$), indicating again the higher steering stability in this condition.

Comparing the uninstructed ("free") condition to "tang" and "gaze," the error values obtained for the former all lie between those for the latter two conditions and are not significantly different from them, indicating that strategies of comparable quality are used by subjects in everyday driving.

A similar pattern was obtained for the distance between the car and the right lane markings (Figure 5B). On average, subjects drove closer to the lane markings both

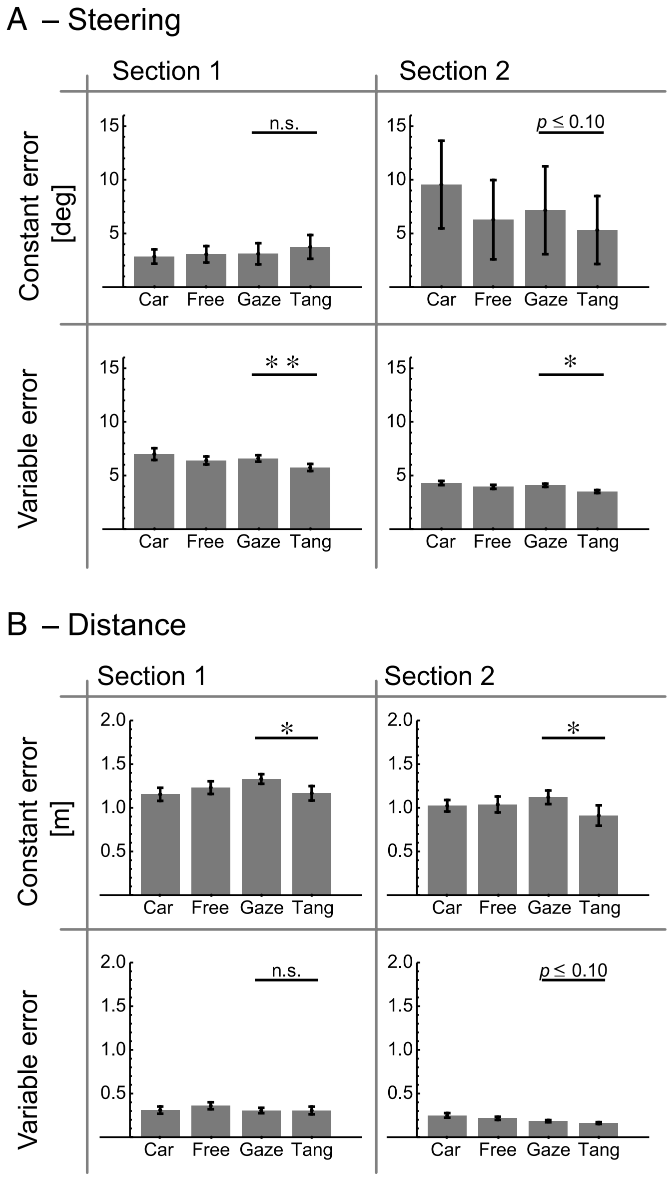

Figure 5. Driving behavior under enforced strategies. (A) Deviations of the steering wheel angle from the set point given by the construction of the street. The four insets show the constant and variable error (± 1 *SEM*) for the first and second section of the loops. (B) Analogous data for the distance to the right lane marking.

when turning into the curve (Introduction) and when steering in the curve (Materials and methods) in the tangent point condition compared with the gaze-sampling condition (Randomization tests, $Z = -2.32$, $p = 0.010$ and $Z = -2.24$, $p = 0.125$, respectively).

The variable error for the distance is in contrast very small with values between 0.2 and 0.3 meters. In view of that the distance is measured with a resolution of 0.1 m, it may not be too surprising that none of the error differences became significant.

As already observed for the steering data, the error values obtained for the uninstructed condition ("free") lie halfway between those for "gaze" and "tang." Thus, in the "free" condition subjects drove more variably than in the "tang" condition, i.e., more variable than they could in principle. The analysis of eye movements in the free" condition showed gazes to the tangent point in 75% of the time, less often than in the instructed "tang" condition. The difference in driving quality observed between the two conditions might therefore suggest that subjects were a bit more liberal in their steering intentions in the "free" condition, and allowed some distractions to interfere with the steering strategy.

To underpin these results, we analyzed eye movements performed in the two instructed conditions. Eye data reveal that subjects actually complied to the instructions in 90 to 98% of the time, with infrequent glances to other spots in the world outside the car. This leaves open the possibility that, even when instructed to rely on gaze sampling, subjects actually based their steering actions on the information gathered during these short glances to the tangent point, or vice-versa. However, even if subjects did so, this would only reduce the differences between conditions and thus the significance of the statistical tests applied (i.e. a conservative effect).

## Ease of driving with the different strategies

When asked informally for the stress associated with employing the strategies under investigation here, subjects all reported that the gaze-sampling strategy was the most tiresome by far. However, strong fixation of the tangent point came second as it required the suppression of eye movements. Informal as it is, this result fits the eye movements we observed in the "free" condition, namely that subjects check the position of the tangent point in a regular pattern of longer glances and, in between, look elsewhere.

# Discussion

In summary, we let nine subjects drive a test car through the loops of a motorway junction while we recorded their eye movements and car-directed actions. The test was split into three parts. In the first part subjects remained uninstructed as to their driving strategy in order to observe where they look and thus which strategy they use spontaneously. In parts 2 and 3, we instructed drivers to solely use either the tangent-point or gaze-sampling method.

The major result for the first part is that uninstructed drivers rely on the tangent point as the major orientation mark. On average they looked toward it for about 75% of the time. While gazes onto the street occurred in 15% of the time, during these periods no subject ever followed fixated points on the future path actively on their own account but rather stared at the street with a constant angle.

## Differences between gaze-sampling and tangent point conditions

The fact that subjects looked in the direction of the tangent does not necessarily mean that they used this as a marker for their steering behavior. In the second part of the study we therefore used an experimental approach with explicit instruction to use either the tangent point or the gaze sampling strategy for steering. In this direct comparison between the tangent-point and gaze-sampling conditions, we found evidence for the hypothesis that driving with the tangent point is smoother and more stable than driving using the gaze-sampling method. Drivers instructed to look solely at the tangent point as an orientation for curve driving drove closer to the ideal curvature (smaller constant error) as well as smoother, that is with less unnecessary steering variation (smaller variable error). The same holds true for the car's position in the lane, measured by the distance to the right lane marking. As one would probably expect with an orientation to the tangent point and hence to the right, the car is driven closer to the right lane markings. But furthermore that position is held more stably as indicated by the data. The single exception from these results of smaller errors in the tangent-point conditions, namely the higher constant error of the steering in the first segment of the loops, is explainable in terms of the drivers starting significantly earlier into curves in the tangent-point than in any other condition, an action making even the transition between straight and curve driving smooth.

The higher constant and variable steering errors in the gaze-sampling conditions seem to stem from a repetitive pattern of short periods of oversteering, followed by longer periods of understeering. Averaged across the whole trial this results in a gross understeering and higher variance.

## First glances and steering

When subjects approach a curve, two to three seconds before the actual start of the curve, they start glancing to points on the right lane marking just about eight to ten meters ahead, presumably in order to check whether the curve is yet about to start. A distance of eight meters corresponds to about half a second of time, so there would be enough time to plan and execute the necessary steering maneuver if the curve actually started at that point.

Only at the moment of turning the steering wheel did our subjects look directly to the tangent point. This finding seems to be in contrast to the findings obtained for the 'tangent point' condition and to earlier proposals, according to which the glance to the tangent point itself appears about 2 to 3 seconds before the turning into the curve. However, if drivers started looking directly at it at a greater distance they would probably also feel impelled to start steering directly, that is some 40 m early and would thus leave their lane beforehand to the right, which is much earlier than the advance of about 4 m we found.

## Behavior in the free driving condition

Our subjects drove some 24 to 32 loops in the "free" driving condition, i.e. uninstructed. Freely viewing subjects made fewer looks to the tangent point in the initial trials (60% of all fixations), and increased their tendency to look at the tangent point as trials were repeated almost up to the level of the instructed condition (84% of all fixations in the "free" vs. 95% in the "tang" condition). At the same time, the amount of fixation on the road ahead were reduced from approx. 25% in the initial trails to 4% in the later free trials. A possible explanation might be that drivers were initially interested not only in the tangent point for steering but needed to monitor other parts of the road, for example to check for obstacles. As they became more familiarized with the curves the need to monitor the road decreased. Alternatively, drivers may have shifted their steering strategy from one with less usage of the tangent point to one that relies more on the tangent point over the course of the experiment. This latter alternative would mean that drives in unfamiliar situations make less use of the tangent point and rely on other steering strategies. However, even in the initial trials drivers spend two-thirds of their time looking at the tangent point.

Furthermore, the free-driving and the enforced tangent point conditions also differed with respect to the driving behavior. In the tangent point condition, drivers started steering earlier and drove closer to the curb than in the "free" condition. On the one hand, this shows that focussing on the tangent point led to overall better curve driving, but on the other hand one must ask why subjects drove less good in the "free" condition. One possibility is that they used different strategies and, more explicitly, did not use the tangent point strategy in the "free" condition. The observation that most looks (75%) in the "free" condition were directed to the tangent point seems at odds with this possibility, but cannot rule it out. Another possibility is that drivers in the "free" condition did not intend to perform optimal steering maneuvers because their normal steering behavior was good enough. In this case, too, one cannot know exactly which strategy drivers followed during free driving. As mentioned in the introduction, there are more possible strategies than only gaze-sampling and tangent point viewing. However, the observation that the amount of tangent point viewing (low for the "gaze" condition, high for the "free" condition, and almost exclusive for the "tang" condition) correlated with steering quality indicates that the tangent point strategy plays a role in free curve negotiation.

Generally, driving on unfamiliar roads often requires more than just curve negotiation. Thus, drivers need to monitor other parts of the road to not ignore interfering information such as upcoming traffic, junctions, obstacles, etc. The fact that the task was more stressful in the "tang" than in the "free" condition (though not as much as in the "gaze" condition) suggests that subjects felt uncomfortable in suppressing looks to more elements in the scene.

Although our drivers gaze behavior differed between the initial and the later "free" trials, we did not find any particular adaptation effect in the steering or distance parameters. Neither did we find any such adaptation effect in the data for the enforced-strategy conditions "tang" and "gaze," presumably as a consequence of the low number of repetitions. As there were twelve to sixteen loops per condition, this meant that each driver passed each individual loop only three or four times.

## Comparison to other studies

We used a similar approach as Land and Lee (1994) and Underwood, Chapman, Crundall, Cooper, and Wallen (1999). Subjects drove on real roads through a number of blind (closed) curves with invisible endings. During the first few trials subjects looked more on the street surface ahead of the car than to the tangent point, thereby confirming data obtained by both Underwood et al. (1999) and Wilkie and Wann (2003a). However, thereafter the reliance to the tangent point rose permanently up to 80–90%, a figure more consistent with Land and Lee's (1994).

Robertshaw and Wilkie (2008) raised the concern that looks to the tangent point might indeed be rather directed to the point on the lane beyond the bend, a possibility that would favor their idea of gaze sampling. However, due to the fact that the motorway junction loops always rise or fall we can distinguish these gaze targets and can confirm that gazes were indeed all going to the tangent point proper and not to any point on the future lane in the same line of sight.

Furthermore there seem to be some critical systematic differences between studies performed in virtual realities vs. real streets. In a recent study, Robertshaw and Wilkie (2008) conducted a virtual-reality experiment similar to our real-road study of curve driving under free as well as restricted eye gaze conditions. They asked subjects to negotiate curves on computer monitors while either driving normally (their experiment 1) or using exclusively either the gaze-sampling or else the tangent-point method (their experiment 2). In disagreement with our study, they neither found any evidence for "extensive tangent point fixation" in the uninstructed condition nor any advantage as to "more accurate steering" related to enforced tangent-point usage.

In order to account for the differences between the findings we would suggest that the main differences between our studies arise from the difference between real-road and virtual environment experiments. In laboratory-based experiments in which subjects are seated in front of monitors and, presumably even with their head supported by a chin rest, the retinal flow is largely undisturbed. Under these conditions, the extraction of flow lines and the assessment of their curvature seem to be a reliable possibility for negotiating curves. In addition, the street layout used in these environments is rather patchy and thus offers many good features to look at. Furthermore the speed used in these experiments is both, fixed and rather slow, thus doubly supporting drivers in the use of the gaze-sampling procedure.

In contrast, during the test drives on real roads, the driver's head, body and seat normally move irregularly up and down and to side. Although optic flow and gaze sampling can be very useful even in conditions in which the head moves around, for practical reasons the retinal flow becomes increasingly difficult to measure as the eye and head movement becomes more variable. This adds to the noise in the motion measurements and may hinder the use of gaze sampling. Additionally, the speed used here was approximately 16 to 19 meters per second, twice as fast as in the simulations and dependent on the driver and his intended maneuvers. In our view, the variability in flow and speed together with the higher average speed may introduce error factors potent enough to render gaze sampling unreliable as a method in real-word scenarios. Thus we conclude that although subjects succeeded in driving adequately using the gaze-sampling method, relying on the tangent point is probably the safer way to drive on real streets. However, the case may be different for driving in places with no lane-markings or other reliable boundaries. There, curve driving has indeed to rely on other methods. It should be noted here again that optic flow in this case may be used in several different ways, of which gaze sampling is only one. Continuous monitoring of instantaneous heading and its deviation from the goal is another, more general, method to use optic flow for steering (Warren, 1998), and also other methods that make use of the optic flow's information on self-motion are likely to be useful. It is also conceivable that looking toward the tangent point, which is in the in the vicinity of the current heading direction, may ease computations of optic flow for strategies other than gaze sampling. Thus, from our results we can not establish as to what exactly makes looking at the tangent point so reliable. It seems, however, logical to look at it if you want to use its retinal position for steering control.

The tangent point strategy works by registering the angle between the straight ahead direction of the car and the tangent point of the road, and adjusting the steering angle accordingly. Measuring the angular distance between the direction ahead and the tangent point direction is a simple retinal task that could be done in principle without particular gaze involvement (Wann & Land, 2000). Thus, fixations on the tangent point would not appear necessary to solve this task, nor would fixations on the tangent point necessarily mean that the driver uses it for the steering maneuver. The argument from previous work is really an implicit one: drivers were found to look very frequently at the tangent point indicating that it must have a role in curve negotiation. Our experimental approach in this study goes a step further in demonstrating that explicit experimental manipulation of the gaze behavior influences driving parameters, and that an enforcement of the tangent point strategy leads to improved curve driving. This suggests that there is a connection between gaze direction and steering control. Thus, although from the view point of visual analysis, looking at the tangent point might not have much advantage over looking straight ahead for estimating the angle between the two, a tighter connection appears from the view point of sensorimotor coupling, since, for example, the angle of gaze when looking at the tangent point is correlated with the angle between the straight ahead and the tangent point.

### Eye movements as an indicator for action

Finally, we confirm in a slightly modified manner a finding described before by Land and Lee (1994). They reported that subjects indicate going into a turn by a glance to the tangent point two to three seconds before they start turning the steering wheel. Here we find that some subjects do so but that others repeatedly look at the inner lane marking with a fixed angle to the heading direction of the car of about 30 to 45 degrees and start looking at the tangent point only at the very moment of steering. We conjecture that these glances to the side markings represent a check of whether the curve has yet started. With the parameters given in that car, an angle of that size corresponds to a headway of half a second, giving enough time to start the maneuver exactly in time.

## Conclusion

We find that the tangent point method is both the default strategy of negotiating curves in our subjects and the strategy allowing subjects to drive more easily and smoothly through the curves. In contrast to virtual-environment studies, the tangent-point thus wins out against gaze sampling in these real-world experiments.

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## Footnotes

[1] Analysis of the eye movements of the remaining three subjects revealed that they tend to look at the car ahead if it is close and rely on e.g. the tangent point if the car is farther ahead. However, parameters differ strongly between subjects and trials.

[2] In normal curves on country roads, it is quite common that drivers cut corners. This maneuver allows the driver to reduce the steering action to a minimum and keep the velocity nearly unchanged. However, as the loops here comprise angles of 270 deg, cutting curves is not a feasible method.

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