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Optokinetic nystagmus is elicited by curvilinear optic flow during high speed curve driving

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ABSTRACT

When analyzing gaze behavior during curve driving, it is commonly accepted that gaze is mostly located in the vicinity of the tangent point, being the point where gaze direction tangents the curve inside edge. This approach neglects the fact that the tangent point is actually motionless only in the limit case when the trajectory precisely follows the curve's geometry. In this study, we measured gaze behavior during curve driving, with the general hypothesis that gaze is not static, when exposed to a global optical flow due to self-motion. In order to study spatio-temporal aspects of gaze during curve driving, we used a driving simulator coupled to a gaze recording system. Ten participants drove seven runs on a track composed of eight curves of various radii (50, 100, 200 and 500 m), with each radius appearing in both right and left directions. Results showed that average gaze position was, as previously described, located in the vicinity of the tangent point. However, analysis also revealed the presence of a systematic optokinetic nystagmus (OKN) around the tangent point position. The OKN slow phase direction does not match the local optic flow direction, while slow phase speed is about half of the local speed. Higher directional gains are observed when averaging the entire optical flow projected on the simulation display, whereas the best speed gain is obtained for a 2° optic flow area, centered on the instantaneous gaze location. The present study confirms that the tangent point is a privileged feature in the dynamic visual scene during curve driving, and underlines a contribution of the global optical flow to gaze behavior during active self-motion.

1. Introduction

Driving is an intensive visual task (MacDougall & Moore, 2005) which still contains many unknown determinant factors (see Owsley & McGwin, in press, for a review). Thus, the specific curve driving situation has been the subject of several studies, trying to understand the crucial cues in the dynamic visual scene during curvilinear self-motion (e.g. Godthelp, 1986; Warren, Mestre, Blackwell, & Morris, 1991) and questioning the role of the optical flow field (see also, Wilkie & Wann, 2003a). This topic remains under debate and a significant contribution was made by Land and Lee (1994). They were among the first to record gaze behavior during curve driving on a winding road clearly delineated by edge lines. They observed that drivers made gaze fixations toward the inner edge line of the road, near a point they called the tangent point (TP). This point is the geometrical intersection between the road inner edge line and the tangent to this one, passing through the subject's position. They observed that drivers made a saccadic movement toward this point one or two seconds before turning the steering wheel and regular fixations around this point throughout the bend. These observations have been confirmed by many other studies (Chattington, Wilson, Ashford, & Marple-Horvat, 2007; Kandil, Rotter, & Lappe, 2009; Wilkie & Wann, 2003b) with more accurate gaze recording systems. Thus, the study of gaze behavior suggests that the tangent point area contains useful information for vehicular control. First, in geometrical terms, the TP is a singular point from the subject's perspective point of view, where the inside edge line optically changes direction (Fig. 1). Secondly, with reference to the optical flow pattern, the tangent point corresponds to a minimum of optic flow speed in the driver's visual scene when the vehicle trajectory is aligned with the borders of the road (Fig. 1).

Some other observations prevent us from accepting these assumptions as they are. Indeed, as soon as the driver steers the vehicle, the TP is not fixed anymore in the dynamic visual scene but is constantly moving, because its angular position in the visual field depends on both road geometry and car trajectory (Fig. 2). Thus, this point is a source of information at the interface between the observer and the environment: an "external anchor point", depending on the subject's self-motion with respect to the road

Acronyms: SD, standard deviation; TP, tangent point; RC, radius of curvature; OKN, optokinetic nystagmus; SP, slow phase.

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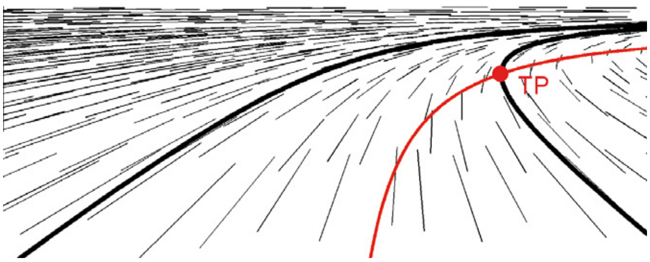

Fig. 1. Optical velocity field generated by a circular movement parallel to the ground plane and aligned with road geometry. The edge lines of the road are represented by continuous black lines and the tangent point location by a red dot. We also display a virtual line (red) corresponding to an inflexion of the lateral component of optic flow velocity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

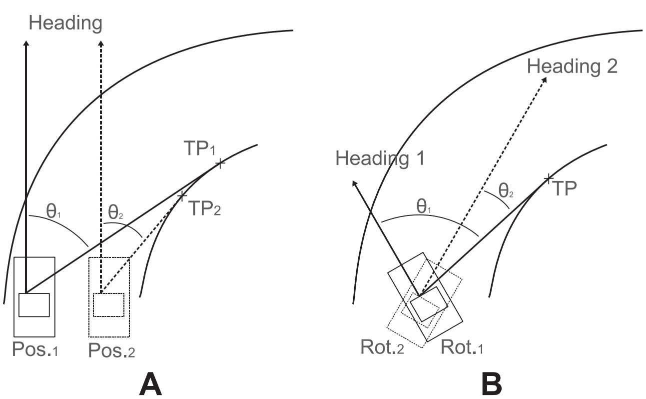

Fig. 2. The angle between tangent point direction and current heading of the vehicle (θ) depends on vehicle lateral position (A) and orientation (B) in the curve. (A) For a given heading, an increase of the lateral position of the vehicle leads to an increase of θ and therefore to a larger tangent point eccentricity from the driver point of view. (B) For a same driver's lateral position in the curve, a change of the heading direction leads also to a change of the tangent point eccentricity.

geometry. This information was described by Lee (1978) as "exproprioceptive" information, meaning that it comes from the external world and provides the subject with information about his or her own movement. Moreover, the visual detection of a trajectory direction change is optimal when the gaze is directed toward the TP direction (Mestre, 2001). This optimization strategy for picking visual information has been tested with a driving simulator (Mars, 2008; Mestre, Mars, Durand, Vienne, & Espié, 2005) in an interactive situation. It showed that displaying the TP to the drivers might constitute a useful aid for curve negotiation.

The perceptive role of the TP is thus established; but one of the main interests of the TP is its potential role in vehicle control strategies. Some evidence supports that the angle between the tangent point and the car instantaneous heading (proportional to the steering angle) can be used for curve negotiation (Land, 1998). It can be eventually be done in concordance with other information such as a point in a near region of the road (Salvucci & Gray, 2004). Moreover, we know from Wann and Land study (2000) that a gaze-sampling strategy with multiple fixations near the future path of the vehicle can indicate an over- or under-steering with retinal flow information.

Following Coutton-Jean, Mestre, Goulon, and Bootsma (2009), we assume that the driver's strategy is to align his/her trajectory with the road geometry; we thus propose that staring at the tangent point corresponds to monitoring its visual motion and trying to keep it visually motionless. Indeed, when the driver's trajectory perfectly follows the road's curvature, the inside line of the road (and the tangent point location) presents what Gordon (1966) refers as a "steady state appearance". It means that the road edge remains stationary in the visual scene. In this case, all flow motion on the edge is directed along the edge, and will be invisible as long as the edge texture is itself not clearly visible (as in the case of uniform white edge lines). Any visual motion of the road edge (and the tangent point) will reveal a departure of the trajectory from the road geometry. However, the surrounding optical flow around the tangent point always has a non-null velocity. In fact, the TP is the intersection between the inside line of the road and a virtual circle passing through the subject position and the trajectory center of curvature. This virtual line corresponds to an inversion of the lateral component of optic flow velocity (see Fig. 1, Cutting, 1986; Gordon, 1966). The only point where optical velocity equals zero is the geometrical center of the curve (Cutting, 1986). It is unlikely that drivers may use it because its position is orthogonal to the instantaneous heading, hence out of the screen range in a driving simulation such as the one we used. Moreover, the driver being continuously controlling steering (speed and angle), the trajectory is always over- or under-steered with respect to the road geometry, leading to non null optic flow velocity of the TP itself. However, to the best of our knowledge, previous studies have focused on the analysis of gaze-fixation behavior relative to the tangent point location during or when approaching curves (Chattington et al., 2007; Kandil et al., 2009; Land, 1998; Land & Lee, 1994; Salvucci & Gray, 2004). These observations lead us to asking a question. How can a driver fixate a point which (1) has usually non zero optic flow speed? and (2) is immersed in a complex flow field?

A first answer to this question can be found in animal and human studies, which have established that a global optic flow induces eye movements (e.g. Miles, 1998). More specifically, unidirectional optic flow triggers an optokinetic nystagmus (OKN), consisting of a succession of tracking eye movements in the direction of visual motion (slow phase of OKN) and fast resetting saccades in the opposite direction. Between two saccades, slow eye movements occur in order to stabilize the retinal image. OKN has already been observed in complex optic flow displays (Mestre & Masson, 1997). Moreover, the presence of optokinetic nystagmus (OKN), was observed in the context of simulated rectilinear self motion of the macaque monkey (Lappe, Pekel, & Hoffmann, 1998) and humans (Niemann, Lappe, Büscher, & Hoffmann, 1999), featuring radial optic flow patterns (see also Miles, Busettini, Masson, & Yang, 2004). However, as far as we know, OKN was not previously described for curvilinear optical flow fields.

As a consequence, we designed the present experiment with a twofold objective:

(1) We investigated gaze behavior during curve driving, assuming that the study of gaze fixations was not sufficient to fully describe drivers' gaze behavior and to take into account the optic flow constraints on the visual system. More precisely, we tested the general hypothesis that OKN would be observed during curvilinear driving.
(2) Using a task involving driving on a delineated road, we addressed a situation in which it was previously shown that a particular cue, the tangent point, acted as a visual "attractor". We wanted thus to test whether gaze behavior would reflect both ocular following and fixation features in this situation.

2. Method

2.1. Participants

Ten participants (five men and five women; 24–27 years old) participated in the experiment after filling an informed consent form. They all were experienced drivers with an average driving li-

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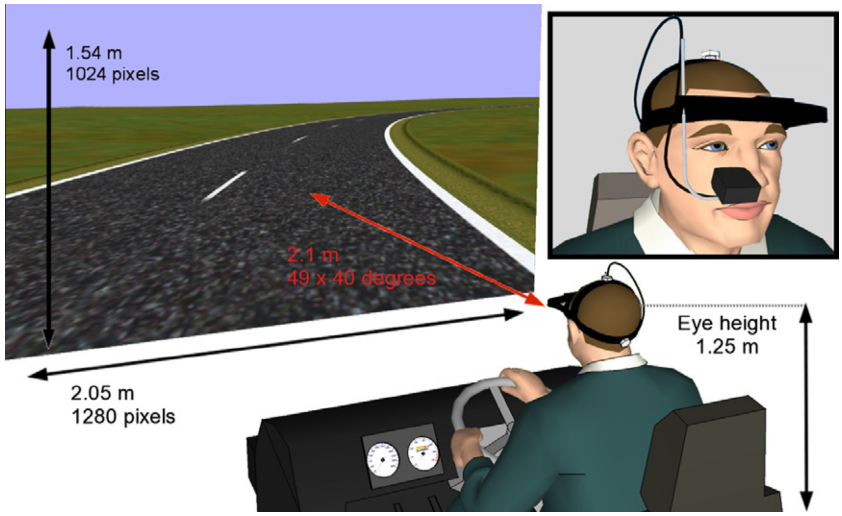

Fig. 3. Setup and visual scene used in the experiment.

cense holding span of 8 years. Only active drivers, for the last 3 years, with normal or corrected to normal vision with contact lenses for myopia, could participate. The experiment was conducted in accordance with the Declaration of Helsinki.

2.2. Apparatus and procedure

Participants drove on a driving simulator developed by INRETS[1] (SIM[2]) and constituted of a mockup, seat, a steering wheel with force feedback, pedals and automatic drive (see Espié, Mohellebi, and Kheddar (2003) for a detailed description). It enables full control of driving scenarios, real time interacting driving, visual and auditory feedback, and on-line recording of simulated trajectories. The visual environment was generated at the rate of 60 Hz and projected on a frontal screen (see Fig. 3). The driver's field of view is compatible with the visual aperture of a windshield in a real driving situation.

The participants drove seven runs, the first trial being for familiarization purposes. They were instructed to drive as fast as possible without ever leaving the right lane (3.5 m wide) of a two-lanes road. The road edge lines were continuous while the center line was discontinuous. The simulated track was composed of eight curves of various radii (50, 100, 200 and 500 m), in pseudo-random order, with each radius appearing in both right and left directions, and separated by portions of straight lines. The visual scene consisted of a textured ground plane, a gray road and green berm (Fig. 3).

The driver's gaze direction was recorded at a rate of 250 Hz throughout the experiment by a helmet-mounted infrared sensor (EyeLink I system, SMI, Berlin, Germany) with a spatial resolution of less than 0.1° and a gaze position accuracy of less than 1° (manufacturer's claim). This video-oculographic system allowed free motion of the drivers' head. A position calibration was performed before every trial with the EyeLink software using a nine-point calibration grid. A real time acquisition system (Keithley Instruments, Cleveland, OH) using in-house Docometer software recorded gaze signal and a pulse derived from the simulation software for each frame displayed. The gaze and driving signals were synchronized off-line at a frequency of 250 Hz.

2.3. Data analyses

For each section, each curve and each trial, the mean and standard deviation (SD) of the simulated vehicle's lateral position and speed were computed. For gaze data, we performed two different analyses, each one focusing on a set of variables specific to curve driving: a global analysis of the solid angle between gaze position and angular position of the tangent point, and a precise description of gaze slow movements relative to optic flow characteristics (speed and direction, see below). These values were calculated for each data point (250 Hz sampling).

Before each analysis of gaze data, eye blinks were automatically excluded from the gaze position signal by an algorithm based on a maximum acceleration criterion. In order to describe accurately gaze behavior with respect to optic flow, we focused on the slow phases of gaze signal (pursuit behavior). To isolate slow phases, we foremost detected saccades with a method inspired from Van Der Steen and Bruno (1995). First, data points were labeled as candidates for saccades if all the following three criteria were fulfilled: a speed threshold of $20^\circ\,s^{-1}$; minimum amplitude of 0.3° and an acceleration threshold of $2500^\circ\,s^{-2}$. In order to precisely detect saccade onsets and offsets, we considered a range from 52 to 8 ms of gaze acceleration before the first labeled point considered, and computed the mean value and standard deviation of this pre-saccadic acceleration. The first point at which acceleration exceeded the mean pre-saccadic ±2SD was considered as a saccade onset.

Each part of the gaze signal between two saccades was first considered as a candidate for slow phase (SP) gaze movements. In order to keep only clear and stable pursuit behavior – for example SP of an OKN – we applied several exclusions. We first assumed that a "real" slow phase does not last more than 1 s, and is positioned on the ground plane of the simulated environment (not on the dashboard or the sky). The parameterization in time of the signal was completed by fitting a linear regression model to the position of each gaze SP, for the horizontal and vertical components separately. The candidates for slow phases were excluded if the root mean square error (RMSE) returned by the fit was too large (i.e. if RMSE > 0.1°). The slopes extracted from the fits (vertical and horizontal components) were used to compute a two dimensional slow phase speed defined as the quadratic sum of the two regressions slopes,[2] for each slow phase gaze movement. We finally computed slow phase direction from the same regression slopes.[3]

[1] Institut national de recherche sur les transports et leur sécurité.

[2] Let a_h and a_v be the regression slopes for horizontal and vertical gaze data. Speed is computed as follow: speed $= \sqrt{(a_h^2 + a_v^2)}$.

[3] A clockwise direction of the slow phase is computed from the regression slopes (a_h and a_v) as follow. If the slopes are both positive, orientation $= \frac{\Pi}{2} - atan(\frac{a_v}{a_h})$.

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In the context of this study, we wanted to investigate the relationships between slow phase parameters and optic flow characteristics. To achieve this, we computed optic flow motion for each gaze position during each slow phase. This local optic flow corresponds to the optic velocity on the screen at a single position: the gaze position. This method elaborates on works by Lappe et al. (1998) and Longuet-Higgins and Prazdny (1980) and consists in three steps. (1) Each (*x*, *y*) point given by the linear fit of the gaze position is expressed in screen coordinates. (2) We computed the optic flow velocity *f* at a foveal position of the gaze (*x*, *y*) on the screen from the instantaneous translational *Tz* and rotational *Ry* velocities of the car in the 3-D environment.

$$f(x,y) = \frac{-y}{Kh}\begin{pmatrix} xTz \\ yTz \end{pmatrix} + \begin{pmatrix} -KRy - \frac{x^2}{K}Ry \\ \frac{-xy}{K}Ry \end{pmatrix} \quad (1)$$

where *K* corresponds to the focal length and *h* denotes the camera height from the ground plane.

(3) We finally computed three different gains: a speed gain (ratio between gaze and local optic flow velocities), an angular bias (angular deviation between local optic flow and gaze orientations) and the total gain defined as the product of the speed gain by the cosine of the angular bias (Lappe et al., 1998).

The pursuit and optokinetic systems are known to integrate motion signals from a larger part of the visual field than the foveal area (Lappe et al., 1998). As a consequence, we computed average optic flow in larger areas (i.e. from 1° to 7°, per 1° steps, and for the entire screen). We finally computed a sum of 1000 optic flow velocities regularly spaced in a circle centered on the gaze position on the screen.

All statistical treatments were conducted with an analysis of variance (ANOVA) without the trial factor by averaging six trials. The significance level was set at $p = .05$. Two main designs were used, either two-way analysis (four radii of curvature and two directions of the curves) or one-way analysis (eight signed curvature; i.e. the inverse of radius of curvature). When necessary, a posteriori comparisons were conducted to determine the nature of the observed effect (Newman–Keuls post hoc tests).

3. Results

3.1. Angular distance between gaze and tangent point locations

The gaze was always located near the tangent point during curve driving (Fig. 4). The average solid angle (across all conditions and participants) between the tangent point angular location in the visual scene and gaze direction was equal to 3.1 ± 1° and was always less than 7°. A two way analysis of variance showed no statistical effect of the direction of the curve ($F(1, 9) = 1.09$, n.s.) but a significant effect of the radius of curvature ($F(3, 27) = 45.45$, $p < .05$, $\eta 2p = .83$). Post-hoc analysis indicated that the distance between gaze and tangent point (TP) was not statistically different for the two large curves (2.35 ± 1.38° and 2.45 ± 1.41° respectively for 500 and 200 radii) and increased for the two sharp curves (3.18 ± 1.88° and 4.59 ± 1.92° for 100 and 50 radii respectively).

3.2. Tangent point movements and control of the vehicle

Even if the gaze-TP distance is limited, one cannot assert that the TP is at a fixed position on the screen. Indeed, sizable fluctuations are observed in the spatio-temporal evolution of the TP position (Fig. 5). The tangent point always moves to an eccentric position at the beginning of the curve, mainly driven by the road topography (i.e. when the driver enters the curve); it then oscillates as a result of driver's lateral position and car orientation readjustments during the curve (see Fig. 2). Indeed, an increase of the radius of curvature of the bend leads to an increase of the horizontal TP eccentricity (Table 1). Moreover, in a single trial and curve, the TP location does not remain at a constant position. The drivers' control of the simulated vehicle's lateral position is reflected in the standard deviation of the lateral position and induces variability of the TP location in a curve (Fig. 2, Table 1).

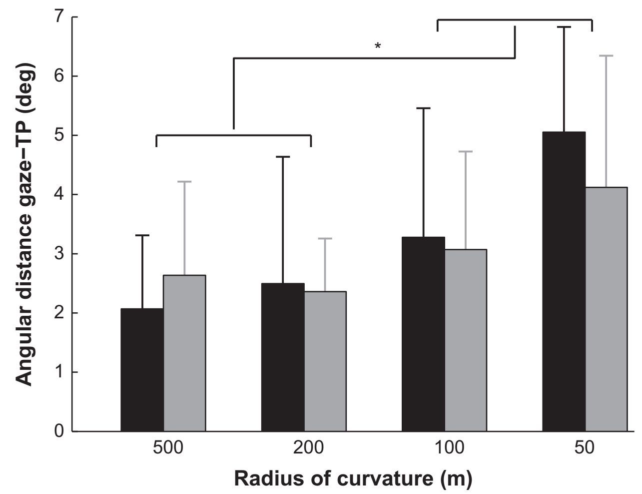

Fig. 4. Average values and standard errors of the angular distance between gaze direction and tangent point position, as a function of the radius of curvature, for left (black) and right curves (gray). The star indicates a significant difference.

On average, the standard deviation (SD) of the lateral position across participants and curves is equal to 0.35 m, which is quite good for simulator driving without previous training (Mars, 2008). A two-way ANOVA shows a main effect of the radius of curvature ($F(3, 27) = 59.93$, $p < .05$, $\eta 2p = 0.87$) on SD of lateral position. According to post hoc analysis, SD of lateral position systematically increases as radius of curvature decreases, i.e. the performance decreases for sharp bends. We can also observe an effect of the curve direction ($F(1, 9) = 17.13$, $p < .05$, $\eta 2p = 0.66$) indicating that performance is worse on left curves (0.37 m), as compared to right curves (0.33 m).

3.3. Gaze behavior

We have previously shown that the gaze position was in the TP area on the screen, even if the TP position can vary during a curve or between curves. However, we observed no dedicated gaze movement to follow the TP variations, neither multiple fixations, nor long or multiple pursuit phases. Instead, we observed a systematic optokinetic nystagmus (OKN). The observed gaze behavior consists of a succession of smooth pursuit eye movements (slow phases of OKN) and fast resetting saccades in the opposite direction (Fig. 5).

The slow phases (SP) clearly do not precisely track variations of the tangent point location. On the contrary, they sometimes happen to be directed orthogonally to the TP movement, and sometimes are in the same direction (Fig. 5). However, the observed OKN has a particularity; the global gaze location targets specifically the TP area during all the curves, and does not explore the entire visual scene (contrarily to Lappe et al. (1998) and Niemann et al. (1999)). Once the SP are detected (Table 2), we determined whether they represent an important part of oculomotor behavior. We labeled ∼10,100 SP for all participants across all conditions, corresponding to ∼21 SP per trial in a bend. These SP constitute half the time of the gaze signal in the curve and are therefore representative of the oculomotor behavior. While the possibility that SP might sometimes be fixations or compen-

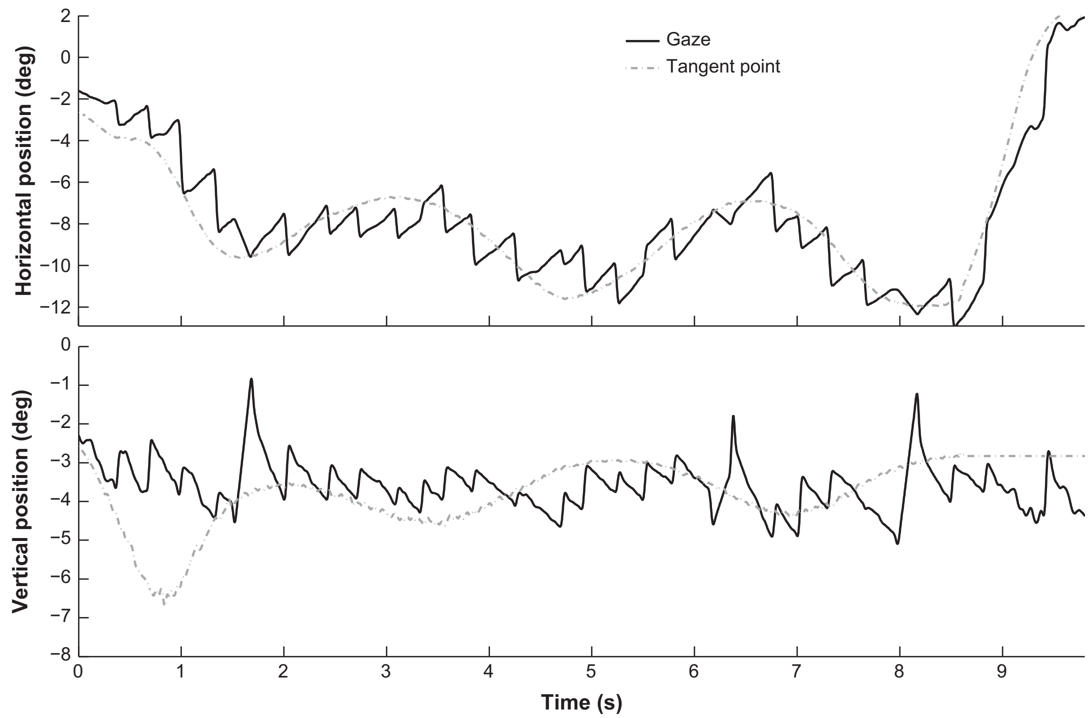

Fig. 5. Representative data for one participant during a left curve of 100 m radius. The standard deviation of lateral position (0.34 m for this trial) is analogue to the population one (0.37). Horizontal and vertical gaze and tangent point position are shown (solid black and broken gray lines, respectively). The zero position indicates the center of the screen and negative values correspond to the left part of the screen for horizontal position and to the ground plane below horizon for vertical position. This figure shows important variations of tangent point eccentricity during the curve, and demonstrates that gaze globally follows this position. At the end of the bend, the TP moves back to a central position on the screen, been indiscernible of the focus of expansion. These different variations of the TP location are globally followed by drivers' gaze. However, we do not notice any fixation or only pursuit behavior, but a clear systematic optokinetic nystagmus downwards and from left to right.

Table 1
Mean and standard deviation between participant of trajectories-related variables as a function of the curves radius of curvature (RC). The participants drove almost at the same velocity in all curves. The mean lateral position of the vehicle is expressed with respect to the inside edge line, and the driver's performance is defined as its standard deviation. We observe an increase of the horizontal tangent point horizontal eccentricity (linked to road geometry) and variability (linked to the driver trajectory) with the sharpness of the curve. Here are also shown the mean optical flow speed at the drivers gaze position on the screen.

RC (m)	Vehicle speed (m/s)	Lateral position (m)	Performance (m)	Horizontal TP eccentricity (°)	Horizontal TP variability (°)	Local flow speed (° s^{-1})
500	37.87 ± 0.52	1.76 ± 0.24	0.24 ± 0.06	4.4 ± 0.32	0.97 ± 0.32	6.56 ± 6.71
200	36.37 ± 0.86	1.63 ± 0.27	0.29 ± 0.08	6.65 ± 0.6	1.47 ± 0.6	8.64 ± 7.07
100	35.93 ± 1.89	1.5 ± 0.24	0.37 ± 0.09	8.51 ± 0.74	2.68 ± 0.74	10.79 ± 7.53
50	33.99 ± 2.94	1.51 ± 0.21	0.52 ± 0.12	11.33 ± 0.78	5.91 ± 0.78	15.82 ± 8.23

satory eye rotation for head movement[4] cannot be excluded, only 82 SP have a speed below 0.5° s^{-1} and 680 SP below 1° s^{-1}. This suggests that the slow phases are in majority pursuit gaze movements.

On average and across all conditions, slow phases last ~370 ± 170 ms with an amplitude of ~1.5 ± 0.9°. This amplitude is comparable to Lappe et al. (1998) results (~400 ms). Amplitude increases monotonically with the sharpness of the bends (0.52°, 1.08°, 1.93° and 2.57° for RC of 500, 200, 100 and 50 m respectively, ($F(3, 27) = 181.51$, $p < .05$, $\eta 2p = .95$). However, amplitudes higher than 4° represent only 5% of the SP distribution. Simultaneously, SP duration decreases when radius of curvature decreases (from 441 ms in RC of 500 m to 261 ms in RC of 50 m, ($F(3, 27) = 50.47$, $p < .05$, $\eta 2p = .84$), and is longer in right curves ($F(1, 9) = 9.73$, $p < .05$, $\eta 2p = .52$), as compared to left curves.

[4] In this experiment, we do not analyzed the eye movement but the gaze movement. In this case, the vestibulo-ocular reflex is not discernible from an eye fixation with the eye fixed.

Table 2
Summary of gaze data analysis for all the participants. Blinks and saccades arc excluded beforehand, from velocity and acceleration criteria. After the selection is applied (see Section 2.3), the slow phases time is found to be half the driving time in curves, thus representative of the gaze behavior.

		No. of occurrence	Mean time (s)	Total time (s)	% time
Blink		818	0.21	170	2.27
Saccade		14,388	0.06	848	11.32
Slow phase					
Too long	} Excluded	1156	1.54	1784	23.82
Out of plane		1247	0.37	462	6.16
Bad fit		1145	0.48	544	7.27
Real slow phase		10,101	0.36	3680	49.15

3.4. Slow phases and local optical flow speed

As a consequence of amplitude and duration characteristics of slow phases, mean speeds of slow pursuit phases during curve driving spread from 1.65 to 12.5° s^{-1}, with an average speed of ~5.61 ± 4.10° s^{-1}. An ANOVA test reveals a major effect of the radius of curvature ($F(3, 27) = 337.29$, $p < .05$, $\eta 2p = 0.97$) on slow phases speed. Post-hoc analysis indicates that the speed of gaze slow phases systematically increases as the radius of curvature decreases. However, there is no curve direction effect on SP speed ($F(1, 9) = 0.217$, n.s.).

The local optical flow speed (calculated for each data point at the participant's foveal gaze location during slow phases) also increases when the radius of curvature (RC) decreases ($F(3, 27) = 337.29$, $p < .05$, $\eta 2p = 0.97$), with no difference due to curve direction ($F(1, 9) = 1.76$, n.s.). Post-hoc analysis confirms a systematic increase in local flow speed as a function of the sharpness of the curve (see Table 1). This increase of local optical flow speed is not the result of a concomitant increase in vehicle speed, this latter diminishing systematically as function of sharpness of the curve (Table 1, ANOVA test: $F(3, 27) = 18.29$, $p < .05$, $\eta 2p = 0.67$). The ANOVA test reveals also a slight vehicle speed diminution for left curves ($F(1, 9) = 18.45$, $p < .05$, $\eta 2p = 0.67$). Instead, local optic flow effects might be explained by the conjunction of three factors. First, the gaze is, on average, farther from TP in sharp curves, inducing a higher local optical velocity (see Fig. 1). Second, the standard deviation of the lateral position of the simulated vehicle is higher in sharp curves (small RC), and therefore the supplementary rotations of the car (induced by steering movements) can cause higher optic flow velocities. Third, the curvier is a bend, the more rotational velocity is added, resulting in overall higher optic flow speed (especially if the vehicle's speed remains constant, which was the case here).

3.5. Slow phases and local optical flow direction

We further expressed slow phase direction in reference to a downward-pointing vertical axis (see Fig. 6 for SP orientation radial distributions). Slow phases in right curves are systematically oriented to the left and vice versa. A one-way ANOVA shows an effect of signed curvature ($F(7, 63) = 230.63$, $p < .05$, $\eta 2p = 0.96$). The more curved are the bends, the higher is the SP orientation. However, there is no significant difference between the orientations in the two sharpest curves.

The local (at gaze location) optical flow direction is less systematic, being oriented to the left in left curves and to the right in right curves of large radius of curvature (500 and 200 m). On the contrary, in the two sharp curves (100 and 200 m), there are then oriented in a direction opposite to that of the curve. This difference of optical flow orientation between large and sharp curves is heavily caused by the dominance of the rotational component of the vehicle's motion with respect to the translational component of the vehicle's motion during the curve.

3.6. Slow phase gains

So far, we have described gaze behavior during curves and detailed the characteristics of SP and optical flow velocities. To express gaze behavior with respect to optic flow characteristics, we now need to investigate the gain ratios between gaze velocity and local optic flow velocity. We therefore computed the gain between local optic flow velocity and gaze speed. The average speed gain of all SP is about $\sim 0.66 \pm 0.45$, indicating that slow phase velocities are a third times slower than local optic flow speed. There is no effect of the curve direction ($F(1, 9) = 1.54$, n.s.) and a significant effect of the radius of curvature on this gain ($F(3, 27) = 31.22$, $p < 0.5$, $\eta 2p = 0.78$). Post-hoc analysis reveals a statistical difference between the two sharp curves of 50 and 100 m radii (0.48 and 0.55, respectively) and the 200 and 500 RC curves (0.77 and 0.85, respectively – see Fig. 7).

We obtain similar results for the angular difference between SP and optic flow orientations. This angular bias is always large, greater than 20° and 90°, in 75% and 23% of the cases, respectively. Here again, we observed no effect of the curve direction but a clear effect of the radius of curvature ($F(3, 27) = 22.62$, $p < 0.5$, $\eta 2p = 0.71$), with a smaller angular bias in sharp curves, with one exception: in the curve of 50 m of radius, the deviation is significantly larger than in the 100 m radius, and is not different from that observed

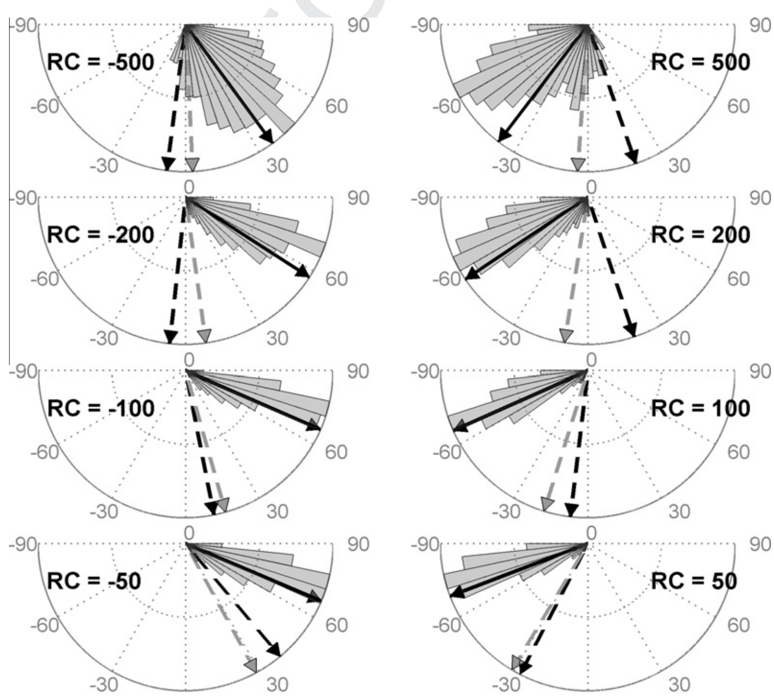

Fig. 6. Mean orientation of gaze (continuous black arrow), local optic flow (broken black arrow) and mean optic flow on the entire screen (broken gray arrow) during slow phases of optokinetic nystagmus. We also show the distributions of all slow phases orientation in gray. Each sub-plot corresponds to one curve, left curves being represented on the left part of the figure. Radii of curvature are ranked from the larger curve (500 m) to the sharpest (50 m).

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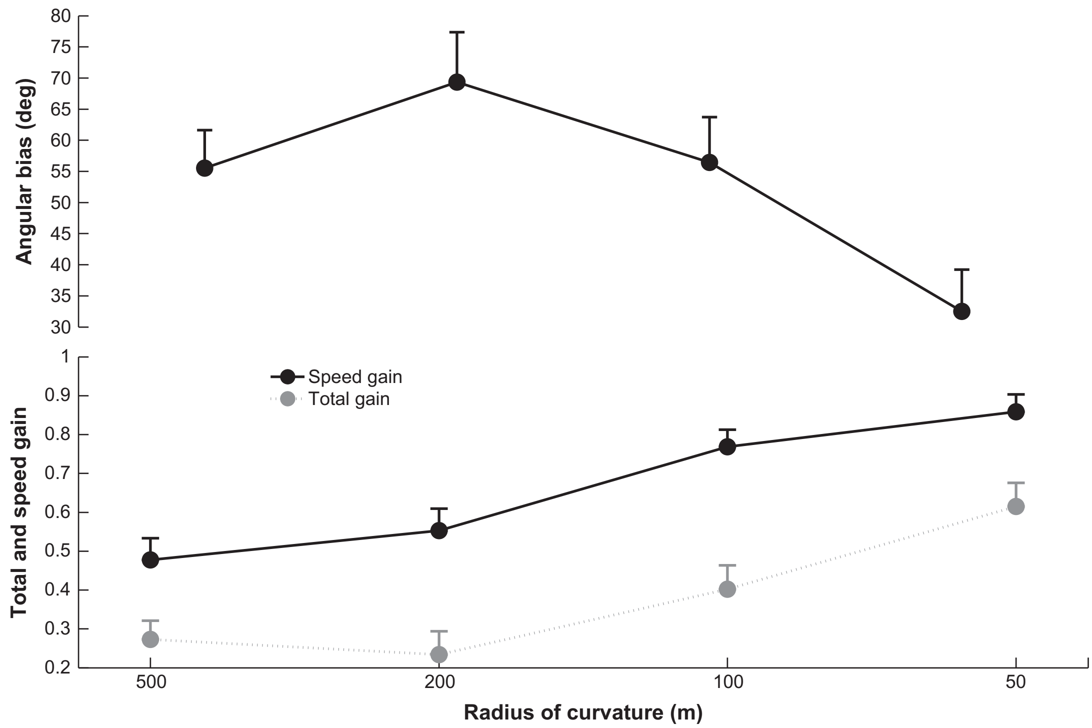

Fig. 7. Representation of the three gains of OKN slow phases as a function of the radius of curvature. At the bottom part of the figure, the black solid line represents speed gain corresponding to the ratio between the gaze speed and the speed of the local optic flow. The upper graph represents the angular bias between local optic flow and gaze orientation during slow phases. The gray broken line shows the total gain during slow phases (defined as the product of speed gain and cosine of angular bias). Bars indicate between-subject standard error.

for the 200 m radius. The total gain (i.e. the product of speed gain and cosine of angular bias) is coherent with the two previous gains, with an effect of the radius of curvature ($F(3, 27) = 32.78$, $p < 0.5$, $\eta 2p = 0.78$). This total gain is higher for sharp curves except for 50 m curves which is not different from 200 m curves and smaller (than the gain) for 100 m curves.

3.7. Global optical flow contribution

The optic flow is not reducible to the local optic flow (at gaze location): we therefore evaluated SP-flow gains with larger circular areas involved for optic flow computation from Eq. (1) (local, 1°, 2°, 3°, 4°, 5°, 6°, 7° centered on gaze position and on the entire screen). We performed a two-way ANOVA with signed curvature factor (eight radii) and nine areas of computation of optic flow factor (nine factors) in order to determine whether we could obtain a better gain for larger areas, as compared to foveal optic flow. For the speed gain, we observed a clear effect of the area size ($F(8, 72) = 149.02$, $p < 0.5$, $\eta 2p = 0.94$). A post hoc test reveals that this gain first increases from 0.66 in foveal area to 0.71 in a 1° area. The gain at 3° is similar to the foveal gain (0.67) and monotonically decreases with larger areas (0.61, 0.55, 0.49, 0.43, 0.38 and 0.17 for 4°, 5°, 6°, 7° and all-screen areas, respectively). The results are totally different for the angular bias (Fig. 7). The same factor of area of optic flow computation is involved ($F(8, 72) = 4.91$, $p < 0.5$, $\eta 2p = 0.35$), but the only statistically different bias is the one calculated from the whole screen surface (40.59°, the minimal value for all areas). We observed that whatever area is considered, this angular bias remains high.

4. Discussion

In this experimental study using a driving simulation scenario, we focused our attention on gaze behavior during curve driving. Departing from previous studies, we demonstrate that the analysis of gaze fixations is not sufficient to comprehensively describe drivers' gaze behavior. Optic flow characteristics have to be taken into account in order to understand pursuit eye movements during curve driving. Analyzing a driving task on a delineated road, we addressed a situation in which it was previously shown that a particular cue, the tangent point, acted as a visual "attractor". We thus wanted to test the assumption that gaze behavior would reflect both ocular following and fixation features in this situation.

4.1. Is it relevant to study gaze-fixation behavior during high speed curve driving?

First of all, global analysis of gaze direction confirms a tendency of uninstructed drivers' gaze to be located in the vicinity of the tangent point (TP), as already shown in real driving experiments (Kandil et al., 2009; Land & Lee, 1994; Wilson, Stephenson, Chattington, & Marple-Horvat, 2007) or experiments realized with a driving simulator (Chattington et al., 2007; Wilkie & Wann, 2003b). These results are fully compatible with the gaze distribution around TP described by Wilson et al. (2007) with a simulator. Their results showed that the gaze was in an area around the TP of 4.4° horizontally and of 3.2° vertically 95% of the time. The present results show that the mean TP/gaze distance was equal to 3.1° and was always less than 7°. In a nutshell, the TP area can be described as a peculiar region of the visual scene, of prime importance during curve driving, and partially constraining gaze behavior.

However, despite the fact that the average gaze position is in the vicinity of the TP, we do not observe a fixation behavior in which gaze would be stable around TP position, but a systematic OKN behavior around the TP. We focused our analysis on pursuit gaze movements in bends (Table 2), in order to address the presence of fixations, smooth pursuit or optokinetic nystagmus

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(OKN). This experiment demonstrates for the first time the presence of OKN behavior during simulated curve driving, when participants are facing a curvilinear optic flow field. This OKN is systematic, with more than 10,000 slow phases in the present experiment, representing more than half the time spent in the curve. In reference to previous studies, this result is in fact not so surprising, since OKN was already observed during (passive) simulated rectilinear self motion in the macaque monkey (Lappe et al., 1998) and humans (Niemann et al., 1999). More recently, the OKN was also observed during stimulated aircraft landing with downward slow phases during rollout (Moore et al., 2008).

Several reasons can explain why previous studies did not observe OKN in a driving situation. First, eye recording systems might not have had the required temporal resolution necessary to distinguish between fixations and OKN (250 Hz in the present study). Secondly, in real driving situations, the real motion and the inertial forces will lead to a more important motion of the head (passive and active; see McDougall et al., 2005) and then to vestibulo-ocular reflex (VOR). In this case, the visual scene will be less stable, and the bumping of the car can inhibit and/or complicate the detection of OKN behavior. We also instructed our participants to drive as fast as possible without straying out of lane. This instruction has lead to an average speed of 36 m/s (~130 km/h) which corresponds to the speed limits on French highways. Moreover, some of our curves (the two sharpest ones) cannot be encountered at such driving speed in every day situations, and the observed OKN might be elicited only at high speed. However, we have observed OKN behavior in our experiment whatever be the curve radius. It remains that real driving analysis of gaze behavior at high temporal and spatial resolution would be necessary to test whether OKN behavior would still be present. Nevertheless, an attentive view on Land and Lee (1994) traces of gaze reveals, in a real driving situation, that a sizable part of gaze movement could be identified as OKN (see their Fig. 1), even though their driving speed where of ~42 km/h. Finally, we do no state that the OKN is the sole gaze behavior during curve driving. Of course, in real life, gaze fixations can be observed toward objects in the environment.

In this article, we demonstrate the limits of fixation analysis to precisely describe gaze behavior during hight speed curve driving, and our study enlightens the non-zero velocity of the tangent point area in the optic flow.

4.2. Optokinetic nystagmus and optical flow

The OKN slow phases (SP) are systematically oriented in a constant direction for each curve: to the left in right curves and vice versa (Fig. 6). We also note that OKN is globally located in the TP area during all the curve, acting in this case as an anchor (or attractor) for global gaze direction and that saccades do not explore the entire visual scene (in opposition with typical OKN elicited by large flow field as for example in Niemann et al. (1999) results). The origin of the mechanism enabling the OKN to track TP location remains unclear, since the saccades of the OKN are not always directed in the TP direction. The TP is yet a salient feature for planning a saccade (with the most extreme horizontal position on the inside edge line). Moreover, the slow phases do not systematically track the direction of TP movements. We emphasized that the TP is surrounded by non null optical flow velocities, even in the ideal case where the driver trajectory is perfectly aligned with the border lines. This optical velocity seems to drive the SP movement. SP amplitude increases for the two sharp curves, which might explain the concomitant increase in distance between gaze and TP position. It is also observed that, during sharp curves, a high rate of rotational component of self-motion, induces high optic flow speed, and thus might explain the increase of speed and orientation of the SP with curvature.

The analysis of OKN slow phases orientation and speed thus suggests that the OKN is elicited by the curvilinear optic flow field. Even if the local speed gain is lower than the gain observed with full-field uniform motion (Masson & Mestre, 1997), local speed gains values are compatible with this hypothesis. These results are compatible with Lappe et al. (1998) and Niemann et al. (1999), who showed low OKN speed gains with rectilinear flow-fields.

From our study of angular bias, and contrary to Lappe et al. (1998), we observed that these gains are poor (above 20° in 75% of the case). Lappe's results, obtained in the context of simulated rectilinear self motion, exhibited a good angular accordance between local motion and gaze direction, with a majority of angular bias less than 20° and a distribution centered on 0°.

As a consequence, besides the fact that OKN slow phases are systematically oriented in a direction opposite to the curve, coherent with the direction of the rotational component of optic flow, the only local flow cannot fully explain SP characteristics. Three explanations are proposed to try to account for differences between Lappe's work and the results presented here.

First, our visual stimulation is completely different from what would be observed during a passive self-motion simulation, at constant rotational and translational velocities, aligned with the road geometry. Indeed, the task of driving requires that the participant controls both speed and direction, and the result is an ever changing optic flow and an optically moving tangent point (TP).

Secondly, the topology of curvilinear optic flow is fundamentally different from a rectilinear flow structure, as it comprises a rich variety of directions and speeds in a single small area of the visual scene (around TP). Even in the case of a perfect trajectory, the local optic flow vectors at the TP static location have a nearly null velocity and a pure vertical orientation on the screen plane. Nevertheless, the optic flow vectors on each side of the TP have opposite directions and asymmetries of speed amplitudes (Fig. 1).

The third specificity of this work is the nature of the task. In this experiment, participants were not instructed to stare at the entire pattern of a stimulus (as in Niemann et al., 1999), or to actively select one motion velocity in the visual scene (as in Mestre & Masson, 1997). Instead, participants had to control the lateral position and the speed of a simulated vehicle (with visual and sound feedback) and were instructed to drive as fast as possible without ever leaving the right lane. Attentional factors are known to alter OKN speed gains (Dubois & Collewijn, 1979; Mestre & Masson, 1997). Even if the driver's gaze is located in the TP area, it is susceptible to be sensitive to optic flow components of another part of the visual field, which on top may have very different characteristics.

A complementary interest of our results is brought by the integration of SP gain in larger areas of optic flow. Previous studies contributed to address the question of the integration of the optic flow in different parts of the visual space: OKN can be elicited by only one degree of visual stimulation (Koerner & Schiller, 1972) and at the same time it is most responsive to a stimulus presented peripherally (Van Die & Collewijn, 1986). In our analysis, the best directional gain is achieved when averaging out the whole screen optic flow, whereas the best speed gain is reached for a 2° optic flow area.

4.3. Effect of road marker on optical flow and gains computation

The correspondence of the direction of the OKN to the direction of the flow remains low, even with large area of integration. We tried here to determine if these results could be imputable to specificities of our road environment, in particular to the white color of the edge markers of the road. Indeed, in our optical flow analysis, we computed "true" optical flow velocity from Eq. (1) in the vicinity of the gaze point, which is theoretically a valid approach. However, the measurement of actual optical flow in the visual system needs luminance contrast. For an extended textured ground

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plane the theoretical flow would match Eq. (1), but if gaze is located near the road marker, Eq. (1) might be a poor indicator of the actual flow. To address this potential bias, we simulated the effect of removing the flow located on the projected inside edge on gains values (Table 3).

Removing the edge line flow leads to a slight increase of both speed gain (2.3%) and angular gain (3.2%). Although the discrepancy between flow and slow phase characteristics is reduced by this approach, it cannot be stated that the texture of the road marker has a major contribution on slow phases characteristics.

4.4. Effect of the curve direction

We do not observe systematic differences between left and right curves in our data. The gaze-TP distance, the local optical flow and SP velocities remain unaffected by curve direction. However, SPs last longer in right curves. As far as trajectory control is concerned, we used a global performance variable: the standard deviation of lateral position. The present results confirm previous data obtained with the same experimental setup (Mestre et al., 2005). Performance is better (smaller deviations) in right curves than in left curves. The visual scene characteristics can partly explain these results. The road interior edge line is continuous in right curves and discontinuous in left curves, and the tangent point location is defined with respect to these lines. Smaller driving performance on left curves can be linked to the discontinuity, and therefore less saliency, of the inside edge line. As for SP duration decreasing in left curves, which could be caused by a supplementary real optical flow velocity linked to edge line discontinuity.

4.5. Slow phase and heading estimation

For rectilinear trajectories, heading can be perceived from the pattern of global optical flow, and/or the location of the focus of expansion (Gibson, 1950; Warren & Hannon, 1988). If gaze direction is aligned with the focus of expansion, the retinal flow field is equivalent to the optic flow field. On the contrary, any gaze rotation (e.g. the gaze tracking an environmental element) adds a retinal slip to the optic flow structure and distorts the retinal flow field, in which the focus of expansion disappears (Regan & Beverley, 1982). A debate opposes two hypotheses: (1) the direction of locomotion can be determined with visual information alone (Warren & Hannon, 1988, 1990) or (2) involves extraretinal eye movements signals (Banks, Ehrlich, Backus, & Crowell, 1996; Royden, Crowell, & Banks, 1994; Von Holst & Mittelstaedt, 1950). Unbiased heading detection can be performed only with small velocities of simulated gaze rotation (below $6^\circ\,s^{-1}$ in Van Den Berg's study (1993)). For a curvilinear trajectory, the focus of expansion no longer exists but accurate heading detection from optical flow is still possible (Warren et al., 1991). In the present experiment, we studied a high speed steering task. Gaze reached high speeds of pursuit in sharp curves (up to an average of $12.5^\circ\,s^{-1}$ for the sharpest one) and rotated around two axes. These results seem to be incompatible with a judgment of vehicle direction with only optical flow visual information and some additional extraretinal information might help drivers recover heading. However, in this complex curvilinear flow field, the SP orientation is more sensitive to global than to local optical direction, and could also provide information about the rotational rate of the car. Besides, SP speed matched only 66% of the local optical flow speed. Lappe et al. (1998), obtained comparable results, and proposed a functional explanation: this behavior could reflect a compromise between foveal image stabilization and optical flow analysis.

Table 3
Effect of a removal of the optical flow localized on the inside edge line on gains characteristics. Values indicate the percentage of enhancement due to the suppression of the flow located on the projected inside edge. We used for the simulation the experimental average values of lateral position, speed and slow phase characteristics. The gaze position is fixed on the TP location and the flow is computed in 2° circular areas.

RC (m)	Speed gain increase (%)	Angular gain increase (%)	Total gain increase (%)
500	3.18	3.14	8.92
200	1.86	3.79	7.76
100	2.56	3.02	11.68
50	1.59	2.86	8.98

4.6. The OKN, reflexive or a part of control?

At this point, a question remains: does OKN contribute anything to the task performance? In other words, is the OKN behavior a better strategy than multiple fixations in the TP direction in order to control the vehicle? In humans, the optokinetic nystagmus mechanism is known for the gaze stabilization from visual motion (Miles & Busettini, 1992). It uses visual tracking in order to reduce retinal image motion. This behavior was mostly studied with *en masse* visual motion and unidirectional flows during long periods. In this case, the SP's OKN gain can be near unity, and was always interpreted as a pure reflexive mechanism, which can be in some case linked to vection (Brandt, Dichgans, & Koenig, 1973). However, when the visual motion became more complex (as in the present experiment with curvilinear motion); a perfect stabilization of the retinal image is impossible, since the optical flow complexity, and the OKN behavior leads to a more complex retinal flow (see Section 4.5).

We found no argument showing that the OKN can be linked to driving performance. On the contrary, the global gaze direction can be sufficient to use gaze direction-based TP steering strategies. Moreover, adding a marker on the TP location enhances the driving performance (Mars, 2008), and this might be due to gaze fixation enhancement and the suppression of OKN. In sum, on one hand, we observe a systematic OKN, which has to be related to stabilization reflexive eye movements. On the other hand, we observe that return saccades always keep the gaze average position in the vicinity of the tangent point. One hypothesis is that, for functional reasons, the driver tries to keep his/her gaze around the tangent point, because it represents an optimal information location. In the same time, the surrounding optical flow triggers reflexive OKN. Experiments in stabilized conditions, if possible, would be required to test for a functional role of OKN.

4.7. Experimental concordance with models of control of vehicle

These results are not equally compatible with all the strategies of vehicle control. The gaze-sampling strategy (Wann & Land, 2000; Wilkie & Wann, 2003b) requires multiple fixations near the tangent point location, in order to perceive over- or understeering from retinal flow information. Our results show multiple slow phase pursuits with poor directional gain, which would distort the retinal flow thus preventing a possible use of a gaze-sampling strategy. On the contrary, a tangent point strategy may be compatible with our observations of the gaze slow movements. This approach echoes recent developments (Elder, Grossberg, & Mingolla, 2009) implementing smooth pursuit into a model of trajectory control.

4.8. Conclusion

Our study confirms that the tangent point is a privileged feature in the dynamic visual scene during curve driving. It suggests that the TP would be a useful source of information to control the vehicle motion. A simple study of saccades in the direction of the TP does not match the strategy observed in the present experiment. Instead, a systematic OKN is observed: it is related to global and local characteristics of the optical flow, underlying the involuntary nature of the eye movements in curves driven by the optical flow. If the OKN is related to the optical flow, it is also observed to be systematically located in the TP area, suggesting a mechanism of minimization of the retinal flow.

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