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The role of edge lines in curve driving

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ABSTRACT

In order to evaluate the role of edge lines in curve driving we examined the steering behaviour in the face of unexpected gradual changes in road geometry. Experienced drivers ($N = 13$) operating a fixed-base driving simulator steered a car along a single-lane (3.80 m or 7.60 m wide) winding road. The experimental track consisted of eight 90° curves with radii of curvature varying between 75 m and 500 m, separated by 500-m long straight line segments. The model-based nature of the simulator was used to create unexpected online changes in road geometry, implemented through a gradual displacement of one or both edge lines while drivers steered around the delineated bend. Although they regulated their speed as a function of road curvature, drivers were found to consistently cut into and out of the curves. When the edge lines did not move, drivers stabilized their lane position during the 20°–70° curve segments, adopting a position closer to the interior edge line for the narrower lane width and smaller radii of curvature. Motion of the interior edge line, whether inward or outward, gave rise to systematic changes in lane position, while motion of the exterior edge line did not affect driving behaviour. Overall, the results point to a visuo-motor strategy of steering based on zeroing-out changes in the rate of change of angular bearing of the tangent point.

1. Introduction

Driving a car along a winding road is a task that requires swift and reliable analysis of spatio-temporal parameters that are necessary to maintain the vehicle on the road. It is generally agreed that distal information provided by vision is fundamental in this kind of task. However, the nature of the visual information used in steering a car around a bend remains an issue of debate. A first conceptual distinction is to be found in the question whether, in order to control steering, the driver needs access to road geometry properties, such as lane width and/or road curvature. Such properties allow defining an "optimal" driving trajectory over the whole curve. Minimal deviation from the middle of the lane (Land & Horwood, 1995; Riemersma, 1981) and minimal lateral acceleration (Boer, 1996) have been proposed as, respectively, optimal safety-based and comfort-based strategies. As demonstrated formally by Land (1998), an estimate of road curvature might be derived from the visual angle between the current direction of motion (heading) and the direction of the tangent point (i.e., the point on the inner lane boundary where the curve changes visual direction). Most authors, however, agree that steering is better understood as based on the direct use of visual information as input variables for control, without requiring the intermediate step of estimating geometrical road properties (cf. Wann & Land, 2000).

A second conceptual distinction is to be found in the question whether, in order to control steering, the driver needs to extract the direction of current heading from optic flow. Gibson (1950) argued that an observer's displacement in a stable

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environment creates a lawful transformation of the visual scene (optical array). Detection of the structure in this dynamic visual field (optic flow) would allow the observer to perceive and monitor the direction of displacement (heading). Heading can indeed be accurately extracted from optic flow during translational (Warren & Hannon, 1988) and curvilinear self-motion (Warren, Mestre, Blackwell, & Morris, 1991). It has therefore often been called upon in models of steering control to provide the visual reference defining the angular bearing of optical characteristics of road structures, such as the vanishing point (apparent focus of expansion of the optic flow) on the horizon for straight road segments or the tangent point for curved road segments (Boer, 1996; Land & Lee, 1994; Riemersma, 1981; Salvucci & Gray, 2004). However, angular bearing (or visual direction) can also be defined with reference to body orientation (Rushton, Harris, Lloyd, & Wann, 1998) or visible parts of the car (Wilkie & Wann, 2002), thereby alleviating the visual system from the difficult task of extracting heading from the flow available at the level of the retina (combining observer whole body displacement with eye movement, see Lappe, Bremmer, & van der Berg, 1999).

Research on the identification of points or zones of particular interest for the control of steering can proceed independent of the hypothesized underlying visual mechanisms. Three lines of research can be distinguished in this light.

In the first approach, theoretical analyses are applied to the dynamics of the visual scene in order to extract salient points (Boer, 1996; Land, 1998; Raviv & Herman, 1992, 1994). Such analyses have pinpointed the tangent point (TP) as a point of potential interest. This is not only due to its inherent characteristics—being the (moving) point of change of visual direction of the inside of the curve—but also to its potential use in the control of steering. Indeed, because a trajectory with a constant distance from the inside of the curve gives rise to a constant angular TP-bearing, a control strategy consisting of zeroing-out changes in angular TP-bearing will give rise to a trajectory minimizing variations in the lateral distance from the inside of the curve (Wann & Land, 2000).

In the second approach, gaze direction is analyzed in order to identify points or zones that are most frequently fixated during driving. In a seminal study examining natural driving along a single-lane winding road Land and Lee (1994) reported that drivers' gaze was predominantly located in a region close to the tangent point. Recently, Kandil, Rotter, and Lappe (2009) reported similar results for natural driving along the cloverleaf curves of motorway junctions. This result has not been systematically replicated during simulated driving tasks (Wilkie & Wann, 2003; Robertshaw & Wilkie, 2008) where participants were found to look more in the direction of the centre of the road than to the inside (but see Mars, 2008b for a counter example). While no doubt indicative of zones of interest, results from gaze fixation behaviour analyses need to be interpreted with care. For instance, a fixation zone may not be reducible to the experimenter-defined salient point it contains, as drivers may fixate the zone for other reasons (see Underwood, Chapman, Crundall, Cooper, & Wallen, 1999). Peripheral vision also contributes to the pick-up of information, for instance in lane maintenance (Land & Horwood, 1995), and the pick-up of information is therefore not restricted to the zone foveated (also see Crundall, Underwood, & Chapman, 1999). Thus, the step from observed gaze direction to inferences about the information detected is not univocal.

By directly influencing available visual information, the third line of research is the most straightforward, deploying an experimental paradigm in which the visual scene is manipulated and driving behaviour analyzed. Utilizing such a paradigm, Land and Horwood (1995) examined driving behaviour when visual access to the scene was reduced to only one or two horizontal segments of 1° high visual angle. In line with the two-level model of steering control proposed by Donges (1978), they found that performance was best when a close and far region (containing the tangent point) were concurrently available.

The present study extends this latter experimental paradigm by examining driving behaviour during online changes in road geometry, implemented by gradually displacing one or both edge lines while the driver steers around the delineated bend. Rather than comparing driving behaviour with and without certain parts of the visual scene available, our experimental strategy thus lies in the analysis of the changes in driving behaviour evoked by continuous changes in road characteristics, without affecting the extent of the visual scene. In so doing, we take the experimental use of (driving) simulators a step beyond current practice. Rather than conceptually limiting ourselves to reproducing reality as far as possible, we take advantage of the model-based nature of the simulated environment by introducing experimental changes that would—for all practical purposes—be impossible to implement during real driving.

The presence of edge lines has been demonstrated to reduce accidents (Taylor, McGee, Seguin, & Hostetter, 1972) while at the same time allowing for a higher speed during curve negotiation (Shinar, Rockwell, & Mallecki, 1980; Zador, Stein, Wright, & Hall, 1987), presumably as a consequence of the richer information provided both in near and far space. In the present experiment, in order to further our understanding of the visual factors underlying the control of steering, we examined driving behaviour in curves of different radius of curvature when (one of both of) the edge lines moved inward or outward, giving rise to continuous changes in lane width and lane position.

2. Method

2.1. Participants

Thirteen experienced drivers, nine men and four women, took part in the experiment. The participants' ages ranged from 23 to 37 years (mean 28.7 ± 4.2 years). All had normal or corrected-to-normal vision and had a driving licence for at least 5 years. The experiment was approved by the local ethics committee.

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2.2. Apparatus

The driving simulator coupled a high-resolution steering wheel (270° maximum rotation) and a set of pedals (both from Extreme Competition Control, Minneapolis, USA) to an in-house developed virtual reality application (ICE software) running on a PC (MS Windows XP Pro©, Intel® Pentium® 4 CPU 3.2 GHz processor, 1.0 Go of RAM, NVIDIA GeForce 6600 GT graphics card). Participants were seated in an adjustable driver's seat, placed 1.57 m (±0.04 m) in front of a large screen (2.3 m high - 3.0 m wide) providing a 75° × 90° field of view. Images were generated at a frame rate of 85 Hz and back-projected onto the screen by means of a Barco IQ 500 LCD projector (1280 × 1024 pixel resolution). The motion characteristics of the car (including lateral acceleration) relative to the virtual environment were obtained by integrating the driver's actions (on the steering wheel, the accelerator and brake pedals) into a dynamic car model. The model included realistic acceleration–deceleration functions as well as an adherence function operating on lateral displacement. A speedometer (with a range up to 200 km/h) was projected at the bottom of the visual scene and a 5.1 surrounding sound system provided an acoustic feedback based on the simulated car engine speed.

The visual scene (see Fig. 1A) included the car's bonnet in the foreground and further consisted of a ground plane, textured with gravel, with two superimposed white continuous lines (0.12 m wide) defining the road's lateral limits. Lane width was either 3.80 m or 7.60 m.

The simulated track was 7.62 km long and comprised eight 90° curves (four bending to the left and four bending to the right) with four different radii of curvature (75, 150, 300, and 500 m), separated by straight line segments of 500 m (see Fig. 1B).

2.3. Procedure

Drivers participated in four sessions of about 1 h each (two for each lane width). In order to get used to the driving simulator (in particular to the car's dynamic model), they completed three training trials before the first experimental session and one training trial before each of the following sessions. During the experiment, participants were instructed to drive as fast as possible without ever leaving the road.

When participants entered a curve, the edge lines could (unpredictably) move inward or outward. Edge line motion was created by gradually increasing or decreasing the radius of curvature of the edge line object in the underlying road model over an amplitude of 1.90 m during a 3-s period. In the control condition, neither line moved. In experimental conditions, the inner edge line, the outer edge line or both edge lines moved. During the initial part of the straight line segment immediately following the curve initial lane width was restored by moving the appropriate edge line(s) in the opposite direction over a distance of 1.9 m during a 3 s interval. Participants performed three trials in each condition with the order of conditions presented in a randomized order. If participants left the lane, the car was subsequently repositioned in the middle of the track and they continued the trial from there on.

2.4. Data recording and analysis

At the end of experiment, all drivers filled out a short questionnaire about the driving simulator (steering wheel, pedals, car's behaviour), the visual environment (track, vehicle, landscape), and the experiment itself.

During driving, position data was sampled at a frequency of 100 Hz all along the track. Off-line processing allowed derivation of pertinent variables describing the car's behaviour, including instantaneous tangential speed, lateral position within the lane, and lateral distance from the edge lines (taking the middle of the front axis of the car as a reference point), as well as optical variables available to the driver, such as the angle θ between the current direction of heading and the direction of the tangent point and its rate of change over time ($\dot{\theta}$). All variables were calculated as a function of progression in curve (sampled at 1° intervals) in order to compare the drivers' behaviour across different conditions (combinations of road curvature, lane width and edge line motion).

For all dependent variables, we calculated, for each individual participant, the average over the successfully negotiated curves in each condition. Dependent variables were then analyzed using Analysis of Variance (ANOVA) with repeated measures on all factors. Factors included lane width (LW: 3.80 m or 7.60 m), radius of curvature (RC: 75, 150, 300, and 500 m), progression in the curve (PC: from 0°—curve entry—to 90°—curve exit—in steps of 10°) and edge line condition (ELC: control, only interior edge line moving, only exterior edge line moving, both edge lines moving). With the significance level set at $\alpha = .05$, we focused on effects that explained a minimum of 2% of the total variance (based on the effect intensity measure *EI*, Abdi, 1987). Significant differences resulting from main effects and interactions were identified using Tukey HSD post hoc comparisons.

3. Results and discussion

According to the questionnaire administered after completing the experiment, only three of the 13 participants had noticed any change in the width of the track at all, with two out of three indicating that an occasional change occurred during the straight road segments. We conclude that, overall, participants were not consciously aware of the experimental changes in road geometry that occurred while they negotiated the curves.

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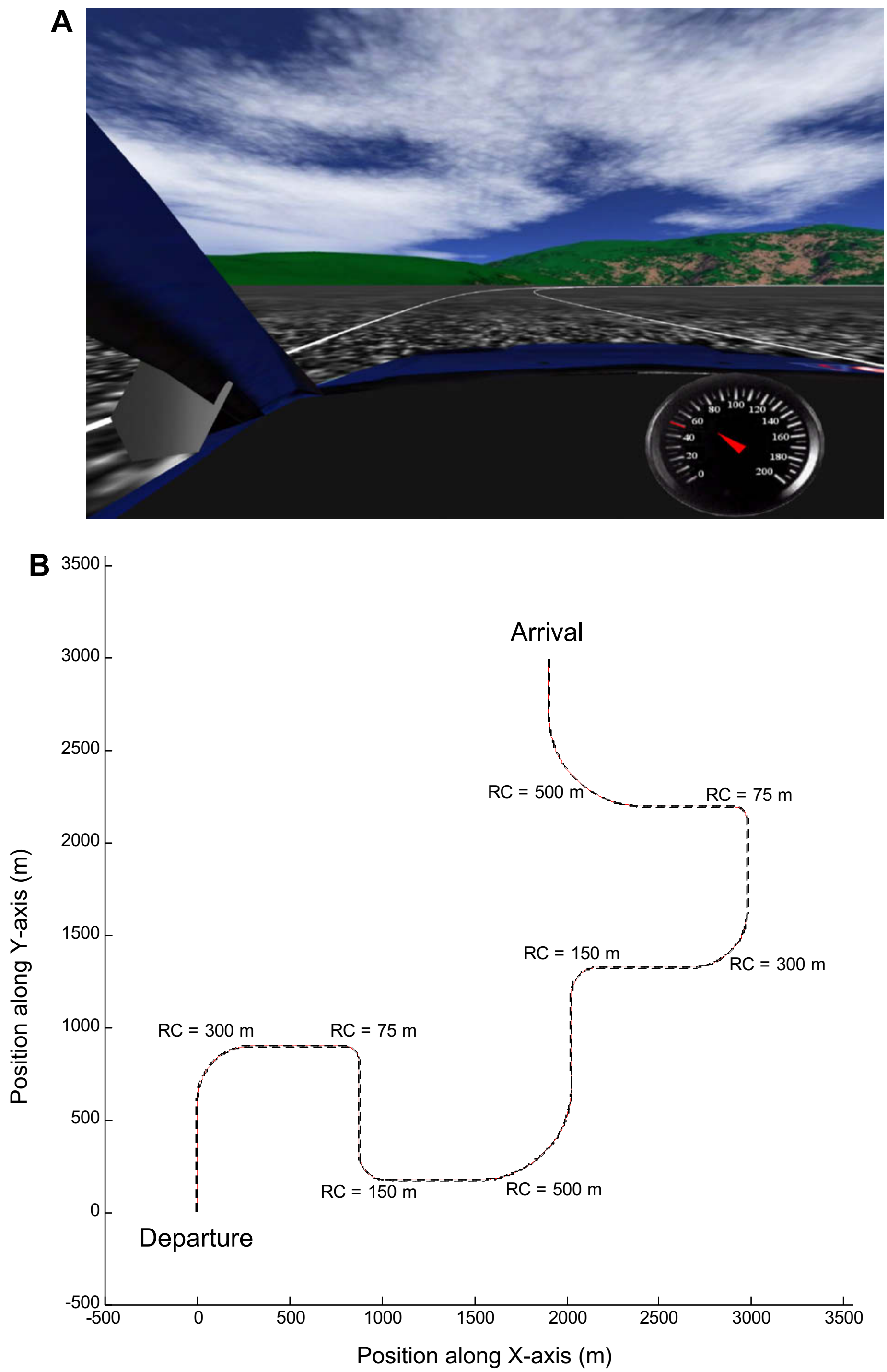

Fig. 1. (A) Screenshot of the visual display used in the experiment. (B) Layout of the track (scale in meters).

Analyses of the driving behaviour included all curves for which the car remained within the track. Overall, lane departures occurred in 5.8% of the curves, most often in the sharpest bends with a lane width of 3.80 m.

3.1. Stationary road conditions

In order to establish a base-line for understanding the effects of changes in the road geometry on curve-driving behaviour we first analyzed the behaviour during control conditions in which the edge lines did not move. Because no differences were found between curves bending to the left and curves bending to the right, data were averaged over the two directions of road curvature.

3.1.1. Driving speed

Driving speed during each curve was primarily affected by the radius of curvature ($F(3, 36) = 324.91$, $p < .001$, $EI = 78.1\%$), increasing from an average speed of 24.1 m/s for the curves of 75-m radius to 44.2 m/s for the curves of 500-m radius. As can

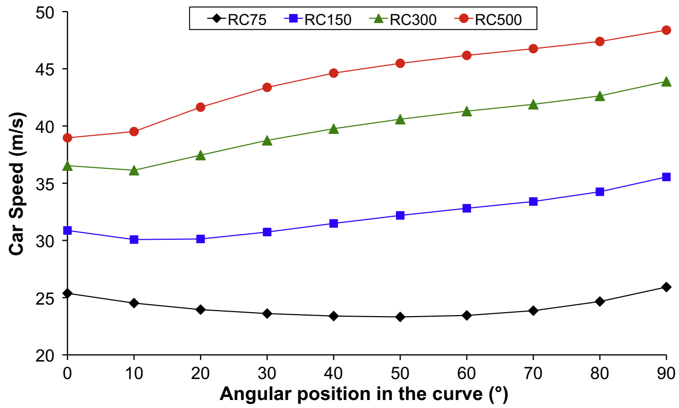

Fig. 2. Average car speed in the control condition as a function of the driver's angular position in the curve for different radii of curvature (RC): 75-m (◇), 150-m (□), 300-m (Δ) and 500-m (○).

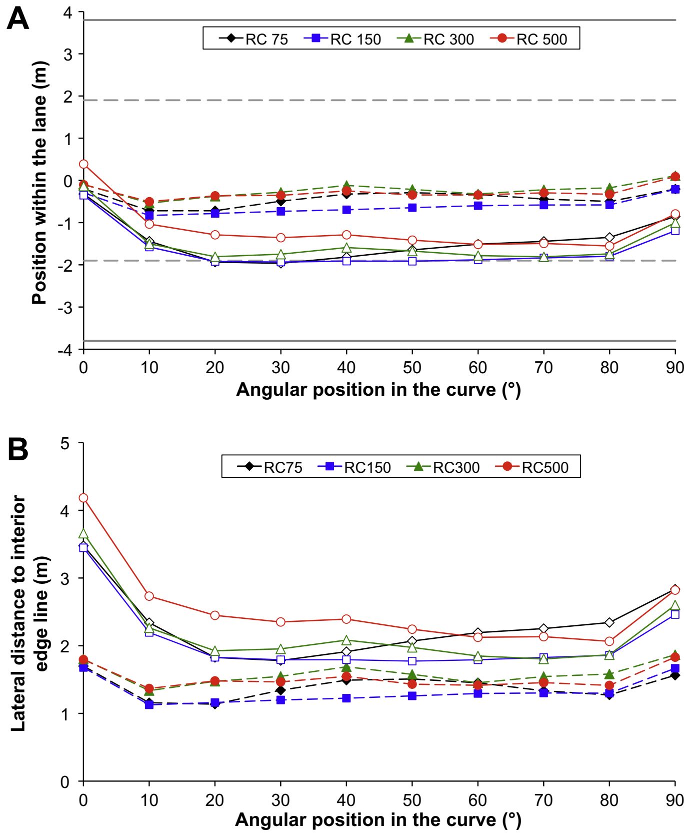

Fig. 3. (A) Average position within the lane in the control condition as a function of the driver's angular position in the curve for different radii of curvature (RC): 75-m (◇), 150-m (□), 300-m (Δ) and 500-m (○) and different lane widths (open symbols and continuous lines: LW = 7.60 m; filled symbols and dotted lines: LW = 3.80 m). Zero represents the centre of the lane. (B) Average lateral distance to the interior edge line in the control condition as a function of the driver's angular position in the curve for different radii of curvature (RC): 75-m (◇), 150-m (□), 300-m (Δ) and 500-m (○) and different lane widths (open symbols and continuous lines: LW = 7.60 m; filled symbols and dotted lines: LW = 3.80 m).

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be seen in Fig. 2, speed also varied to some degree during the curve ($F(9, 108) = 26.53$, $p < .001$, $EI = 4.6\%$), initially decreasing and subsequently increasing for the lower radii of curvature and progressively increasing for the higher radii of curvature ($F(27, 324) = 27.68$, $p < .001$, $EI = 2.2\%$). This pattern of results reflects an adequate adaptation of driving speed to the (road curvature) constraints and thus validates, at least qualitatively, the participants' overall driving behaviour on the simulator, with reference to what occurs in a real situation (Herrin & Neuhardt, 1974; Ritchie, McCoy, & Welde, 1968).

3.1.2. *Lane position during the curve*

As can be seen from Fig. 3A, drivers typically steered into the curve, passing near the middle of the road at curve entry. Mean lane position with respect to the middle of the road at curve entry (0°) was −0.17 m ± 0.29 and −0.11 m ± 0.67 for the 3.80-m and 7.60-m lane widths, respectively. During the curve segment between 20° and 70° they stabilized their position in the lane, as evidenced by the lack of effect of progression in the curve during this segment ($EI < 0.5\%$). However, at −1.69 m ± 0.56 this stabilized lane position was located significantly further from the middle for the 7.60-m wide lane than the −0.42 m ± 0.37 observed for the 3.80-m wide lane ($F(1, 12) = 332.49$, $p < .001$, $EI = 63.6\%$). Radius of curvature had a slight but not systematic effect (see Fig. 3A) on the position in the lane ($F(3, 36) = 6.66$, $p < .05$, $EI = 3.8\%$). Towards the end, drivers steered out of the curve passing at a mean position at curve exit (90°) of −0.05 m ± 0.32 and −0.96 m ± 0.60 for the 3.80-m and 7.60-m lane widths, respectively.

3.1.3. *Lateral distance from the interior edge line*

The analysis of the lateral distance separating the car from the interior edge line confirmed the results reported in the lane position section. Entry into the curve was characterized by an initial reduction of lateral distance from the interior edge line (see Fig. 3B), followed by a stabilization of this distance during the 20°–70° curve segment (evidenced by the lack of effect of progression in the curve during this segment, $EI < 0.1\%$). Although drivers deviated significantly more from the middle of the road when driving in the wider lane (see above), this difference in lane position did not correspond to a similar lateral distance with respect to the interior edge line ($F(1, 12) = 85.72$, $p < .001$, $EI = 28.1\%$). On the average, during this segment drivers maintained a lateral distance of 1.41 m ± 0.36 in the 3.80-m wide lane and 2.01 m ± 0.58 in the 7.60-m wide lane. Radius of curvature also affected lateral distance to some extent ($F(3, 36) = 4.04$, $p < .05$, $EI = 5.0\%$), with a significant difference (Tukey HSD post hoc test) appearing between the curves with radii of 150 and 500 m for lateral distances of 1.52 m ± 0.51 and 1.87 m ± 0.66, respectively.

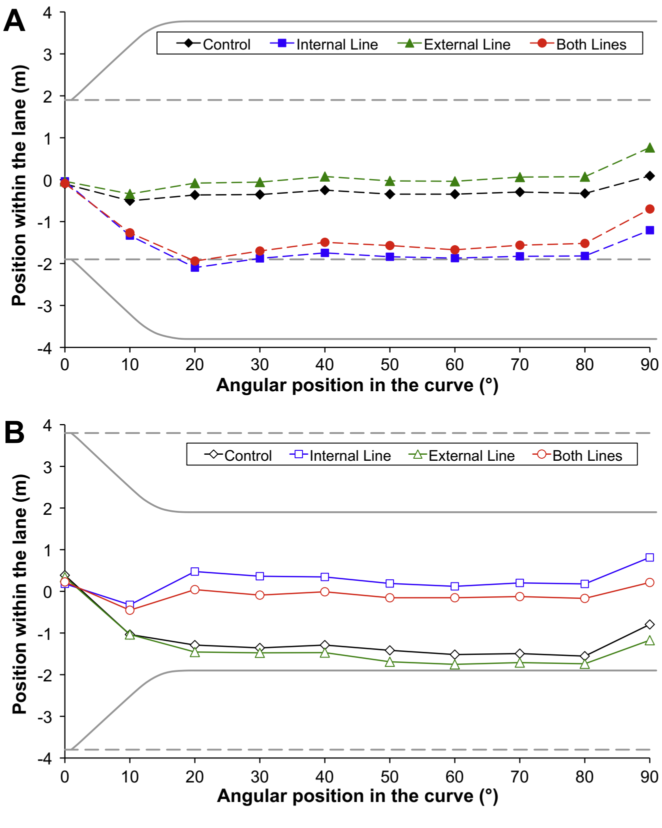

Fig. 4. Average position within the lane as a function of the driver's angular position in the curve of 500-m of radius of curvature. Zero represents the centre of the lane. (A) The 3.80-m initial lane width where edge line motion increased lane width. (B) The 7.60-m initial lane width where edge line motion decreased lane width.

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3.2. Changing lane width conditions

With the curve-driving behaviour under static road conditions having been characterized in Section 3.1, we next analyzed the effects of the changing road geometry conditions, with the inner edge line, the outer edge line or both edge lines moving from the centre outward for the initially 3.80-m wide lanes and inward for the initially 7.60-m wide lanes.

3.2.1. Driving speed

The 3 s of movement of the edge line(s) did not affect driving speed during the curve in any notable way, with the edge line condition main effect as well as its interactions with other factors systematically giving rise to $EI < 0.1$.

3.2.2. Lane position during the curve

The drivers' average position in the lane was affected by the different edge line conditions, varying as a function of lane width ($F(3, 36) = 1773.25$, $p < .001$, $EI = 44.8\%$). Fig. 4 reveals the systematic effects produced for the example of the 500-m radius curves: when the interior edge line moved outward during the curve (initial LW = 3.80 m, top panel), average lane position was shifted outwards and when the interior edge line moved inward during the curve (initial LW = 7.60 m, bottom panel), average lane position was shifted inwards. This effect of motion of the interior edge line occurred whether only the interior edge line moved or both the interior and exterior edge lines moved at the same time. Motion of the exterior edge line alone did not give rise to a noticeable change in lane position.

In all three edge line motion conditions, road geometry changed during a fixed time span (3 s). As can be seen from Fig. 4, for the 500-m radius curves, this time interval corresponded to an average progression in the curve up to 15.3° ± 1.8, after which the edge lines remained stationary and the drivers stabilized their lane position (main effect of progression in the curve: $F(9, 108) = 41.56$, $p < .001$, $EI = 10{,}7\%$). Due to the different directions in the shift in lane position evoked by the inward and outward inner edge line movements, the results revealed an interaction between lane width, edge line condition, and progression in the curve ($F(27, 324) = 370.5$, $p < .001$, $EI = 10.0\%$). Finally, because at the offset of edge line motion drivers had progressed further into the curve for the smaller radii of curvature (on the average, 54.6° ± 4.5, 35.6° ± 2.8 and 23.1° ± 3.6 for the 75, 150, and 300 m radius curves, respectively), a radius of curvature × lane width × progression in the curve interaction was also observed ($F(27, 324) = 48.57$, $p < .001$, $EI = 2.4\%$).

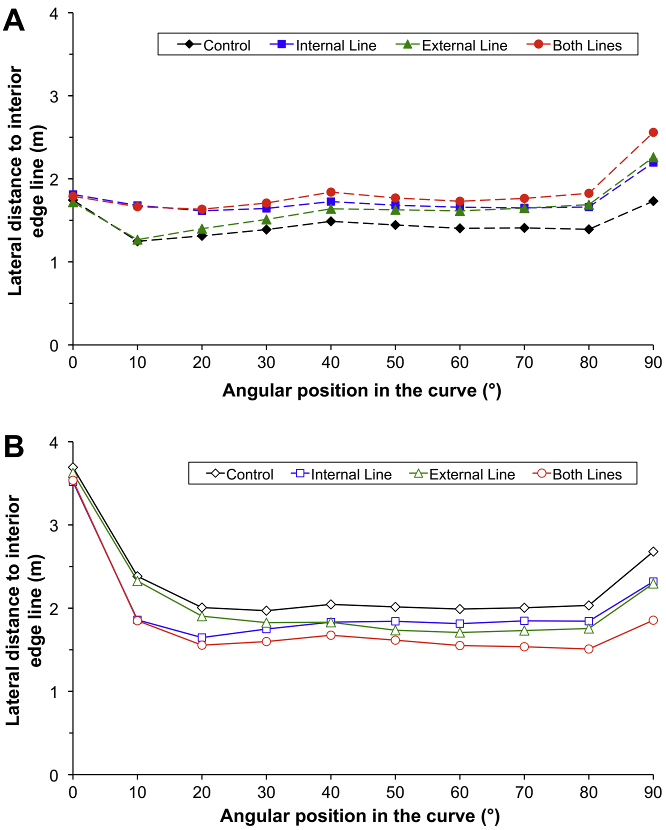

Fig. 5. Average lateral distance to the internal edge line as a function of the driver's angular position in the curve of 500-m of radius of curvature. (A) The 3.80-m initial lane width where edge line motion increased lane width. (B) The 7.60-m initial lane width where edge line motion decreased lane width.

3.2.3. Lateral distance from the interior edge line

As was found for the control conditions, in all conditions lateral distance from the interior edge line varied as a function of radius of curvature ($F(3, 36) = 7.26$, $p < .001$, $EI = 3.8\%$), with larger radii of curvature giving rise to larger lateral distances. On average, lateral distance from the interior edge line was again found to be larger for the 7.60-m lane width than for the 3.80-m lane width ($F(1, 12) = 88.12$, $p < .001$, $EI = 8.0\%$). After entry into the curve, lateral distance initially decreased and then stabilized during the 20°–70° segment, as evidenced by the lack of effect of progression in the curve during this segment ($EI = 0.5\%$). Notwithstanding the fact that drivers systematically changed their position in the lane when the interior edge line moved (see Fig. 4), this change in lane position did not suffice to maintain a constant lateral distance. Edge line conditions affected the lateral distance, varying as a function of lane width ($F(3, 36) = 102,11$, $p < .001$, $EI = 4.7\%$). Fig. 5 reveals the systematic effects of edge line conditions for the example of the 500-m radius curves. Drivers generally followed the motion of the interior edge line, but did not do so perfectly: lateral distance increased somewhat during the outward motion of the interior edge line (e.g., at 10° from 1.37 m ± 0.26 in the control condition to 1.98 m ± 0.35 in the conditions of motion of the interior edge line), and decreased somewhat during the inward motion of the interior edge line (e.g., at 10° from 2.73 m ± 0.54 in the control condition to 2.03 m ± 0.43 in the conditions of motion of the interior edge line). When the interior edge line stopped moving (after 3 s, corresponding to on average progression in the curve up to 15.3° for both the 3.80-m and 7.60-m lane width), drivers stabilized their lateral distance (adapted to the lane width after change) until they began the manoeuvre of steering out of the curve. Motion of the exterior edge line alone did not give rise to a noticeable change in lateral distance as compared to the control conditions.

3.2.4. Optical motion of the tangent point

One strategy for negotiating a curve is to minimize changes in the angle (θ) between the current direction of heading and the direction of the tangent point (Wann & Land, 2000), by continuously seeking to zero out $\dot{\theta}$. We evaluated this strategy by examining $\dot{\theta}$ during the different conditions of the present experiment.

Fig. 6 present the evolution of $\dot{\theta}$ for the different edge line conditions during the exemplary 500-m radius curves. When the edge lines did not move (control condition), $\dot{\theta}$ decreased as expected during the initial part of the curve, reaching a value close to zero around 10°. Moving the interior edge line outward gave rise to an initial increase in $\dot{\theta}$ that was rapidly reduced,

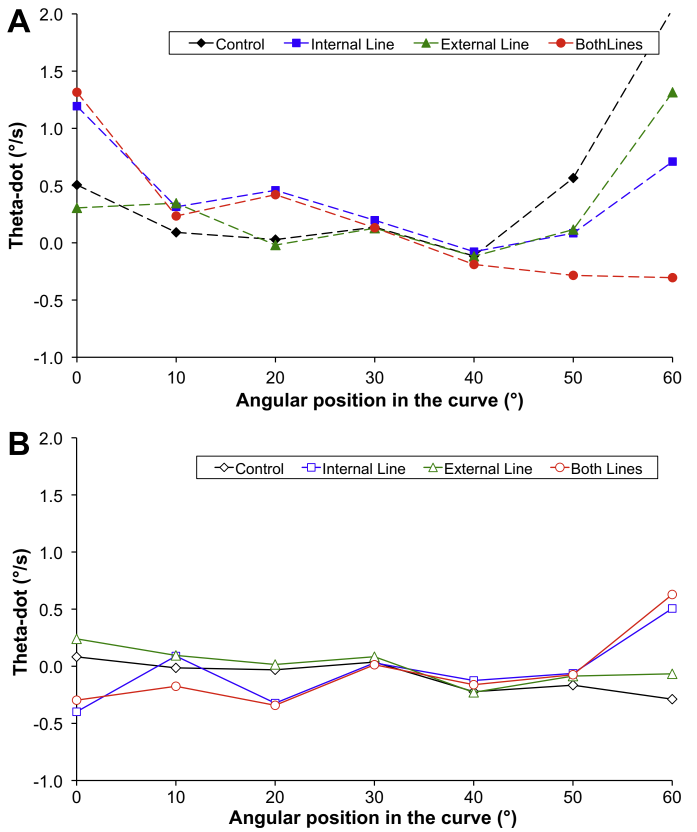

Fig. 6. Rate of change of the angular bearing of the tangent point ($\dot{\theta}$) as a function of the driver's angular position in a curve of 500-m radius of curvature. (A) The 3.80-m initial lane width where edge line motion increased lane width. (B) The 7.60-m initial lane width where edge line motion decreased lane width.

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reaching a minimum around 10° (Fig. 6, top panel). The abrupt end of the interior edge line motion after 3 s (15° progression into the curve in the 500-m RC conditions) resulted in a new rise in $\dot{\theta}$ that, again, was subsequently reduced reaching a value close to zero around 40°. Moving the interior edge line inward gave rise to an initial decrease in $\dot{\theta}$, becoming negative at curve entry. This contraction of θ was rapidly reduced, reaching a minimum value around 10° (Fig. 6, bottom panel). The abrupt end of interior edge line motion after 3 s resulted in a new decrease in $\dot{\theta}$ that, again, was subsequently reduced reaching a value close to zero around 30°. This pattern of results was observed whether only the interior edge line or both edge lines moved. Motion of the exterior edge line only did not affect behaviour, as compared to the appropriate control condition.

Due to lane width differences that can be observed in Fig. 6 (control conditions) and the fact that drivers progressed further into the curve for smaller radii of curvature during the 3 s interval, the effect of interior edge line motion statistically varied as a function of lane width, radius of curvature, and progression in the curve ($F(18, 216) = 6.09$, $p < .001$, $EI = 3.2\%$). Qualitatively, however, the pattern of change in $\dot{\theta}$ was always similar to the one depicted in Fig. 6.

4. General discussion

The goal of the present study was to examine the role of the edge lines in curve driving. We first discuss the general behaviour observed before proceeding to the implications of the behavioural adaptations to online changes in road geometry.

Our results clearly demonstrated that drivers did not remain in the middle of the lane during curve negotiation. During approach to the curve they adopted a position on the outside of the lane and then cut into the curve, passing through the middle at curve entry. After having progressed into the curve up to some 20° they stabilized their position in the lane. Preparation for exiting the curve was accompanied by a new gradual change in lane position, bringing the car back toward the middle of the lane. In the light of the consistently observed cutting into and out of the curves, one should be careful in using measures based on deviations from the middle of the lane (Land & Horwood, 1995; Riemersma, 1981; Robertshaw & Wilkie, 2008; Wilkie & Wann, 2003) as they would not seem to adequately capture driving performance.

Boer (1996) suggested that drivers might follow the path with the lowest maximum curvature in order to minimize the vehicle's lateral acceleration during the curve. Although global minimization of lateral acceleration would require *a priori* knowledge of the curve's geometric characteristics, including degree of curvature and angular extent, the observed cutting into and out off the curves together with the regulation of speed appears compatible with a local strategy of lateral acceleration minimization (also see Reymond, Kemeny, Droulez, & Berthoz, 2001). It remains to be determined, however, whether such results are a by-product of the control strategy deployed or an explicit organizing principle.

In the present experiment, lane width was found to influence the car's position in the lane, with a 7.60-m wide lane giving rise to a further deviation from the middle towards the inside of the curve than a 3.80-m wide lane. A similar influence of the lane width was reported by Robertshaw and Wilkie (2008), who noticed that, notwithstanding their explicit instruction to remain in the middle of the lane at all times, drivers exhibited larger deviations from the middle of the lane when driving in a 6-m than in a 3-m wide lane. Our result revealed that the further inward deviation from the middle observed in wider lanes did not result in a similar lateral distance to the interior edge line, suggesting that both the exterior and the interior edge lines play a role in determining the car's trajectory through a curve.

Exploiting the possibilities offered by the model-based nature of driving simulators, in the present experiment we also examined driving behaviour when road characteristics changed unexpectedly during curve driving. When driving in a 7.60-m wide lane, the edge lines could gradually move inwards (that is, towards the lane middle), either simultaneously or individually. When driving in a 3.80-m wide lane, the edge lines could simultaneously or individually move outwards (that is, away from the lane middle).

When driving in the 7.60-m wide lane, an inward motion of the interior edge line evoked a concomitant change in the car's lane position (Fig. 4b): drivers gradually moved towards and sometimes even beyond the middle of the lane. Of course, the pattern of steering behaviour in this particular situation is not all too surprising in the light of the instruction to remain within the lane boundaries. However, subsequent results indicate that adaptation of lane position also occurred when this was not a necessary consequence of the edge line motion. Indeed, after the offset of the inward motion of the interior edge line (after 3 s), drivers rapidly corrected their inward-moving trajectory, stabilizing the car's position in the lane. The outward motion of the interior edge line when driving in the 3.80-m wide lane brings out the adaptive nature of the steering behaviour even more clearly. In this case, drivers could have continued their progression along their initial path through the curve without any risk of departing from the lane. However, our results demonstrate that they systematically followed the outward-moving interior edge line (Fig. 4a), giving rise to a considerable change in lane position. Once again, drivers rapidly corrected their outward-steering behaviour after offset of outward motion of the interior edge line. This global pattern of results was observed when only the interior edge line moved as well as when both edge lines moved simultaneously. Motion of the exterior edge line alone did not give rise to systematic changes in steering behaviour. Overall, the results obtained in response to edge line motion suggest that, after entry into the curve, drivers regulate the car's position online with respect to the interior edge line.

The pattern of results observed in the moving edge line conditions suggested that drivers acted so as to maintain constant their lateral distance with respect to the interior edge line. However, curve-driving behaviour cannot be reduced to the simple strategy of always seeking a particular lateral distance to the interior edge line: lateral distance was found to vary as a

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function of the radius of curvature, lane width and edge line motion. We therefore suggest that the strategy deployed is not based on bringing lateral distance towards a particular value but rather on zeroing-out changes in lateral distance. What then might be the underlying visuo-motor strategy?

In their two-point visual control model of steering Salvucci and Gray (2004) proposed that drivers use both a near and a far point on the road to simultaneously control the car's current lane position and future trajectory. In their model, the near point—used to monitor lane position and stability—is located in the centre of the lane at some fixed nearby distance from the car current position. The present results clearly indicate that drivers do not regulate steering behaviour with respect to the lane centre: while simultaneous inward or outward motion of the two edge lines leaves the position of the lane centre (and hence the near point) unaffected, it systematically influenced steering behaviour. As the experimental results of Land and Horwood and the modelling results of Salvucci and Gray (2004) quite powerfully suggest that near-point control is operating during driving, the rationale underlying its hypothesized position within the lane needs to be clarified based on the findings of the present experiment.

The far point in Salvucci and Gray's (2004) model represent a salient distant point. Based on the theoretical analyses of Raviv and Herman (1992, 1994), Boer (1996) and Land (1998) the tangent point (TP) clearly qualifies as salient during curve driving. Given that the TP is defined with respect to and located on the interior edge line, it would seem particularly pertinent in the light of the present results. As described by Wann and Land (2000), a control strategy based on zeroing-out changes in angular TP-bearing (captured by the angle θ) gives rise to a trajectory minimizing variations in the lateral distance to the interior edge line. Examination of the time-varying characteristics of the rate of change of the angular TP-bearing (i.e., $\dot{\theta}$; see Fig. 6) during curve driving revealed that drivers consistently steered in such a way that $\dot{\theta}$ tended towards zero. This pattern was invariantly observed, when lane width was 3.80 or 7.60-m, when radius of curvature was 75 m, 150 m, 300 m or 500 m, and when edge lines remained stationary, moved or stopped moving. Our results are therefore highly compatible with a visuo-motor strategy of steering based on zeroing-out changes in the rate of change of angular TP-bearing.

Mars (2008a) recently demonstrated that, compared to a free gaze condition, steering stability was improved when drivers were instructed fixated their gaze on the (continuously visually materialized) TP, in line with the earlier findings of Mestre, Mars, Durand, Vienne, and Espié (2005). However, he also reported that the stability of steering control increased when participants fixated a point characterized by a continuous lateral offset with respect to the TP. In line with the suggestion of Salvucci and Gray (2004) that drivers could use a the angular bearing of a preceding vehicle, Mars' (2008a) results indicate that the far point used need not be limited to the TP. Indeed, any (moving) point positioned at an adequate distance/time ahead of the car might be used for the anticipatory control of steering.

5. Conclusion

Edge lines clearly support the visually guided behaviour of drivers steering around a curve. The characteristics of the driving behaviour observed in this study corroborate the results of earlier studies demonstrating that the tangent point provides perceptual information relevant for steering in curve driving (Land & Lee, 1994; Mestre, Mars, Durand, Vienne, & Espié, 2004; Kandil et al., 2009; Mars, 2008b). Based on the responses to online changes in road geometry, the present experiment indicates that drivers continuously regulate their steering behaviour in such a way that changes in lateral distance to the interior edge line are minimized. Overall, our results are compatible with a visual control strategy based on zeroing-out the rate of change of angular bearing of the tangent point. Hence, as also argued by Rushton and Salvucci (2001), drivers do not need to extract geometric road characteristics, such as curvature, but may safely rely on continuously available visual information.

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