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Gaze and steering strategies while driving around bends with shoulders

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ABSTRACT

The installation of shoulders on rural roads to create more forgiving roads encourages drivers to cut corners on right-hand bends, but the underlying mechanisms are poorly understood. Since eye movements and steering control are closely coupled, this study investigated how the presence of a shoulder influences drivers' gaze strategies. To this end, eighteen drivers negotiated right-hand bends with and without a shoulder on a simulated rural road. In the presence of a shoulder, participants modified their visual sampling of the road by directing their gaze further inside the bend. At the same time, their lane position was deviated inward throughout the bend and the vehicle spent more time out of the lane. These results suggest that the shoulder influences the visual processes involved in trajectory planning. Recommendations are made to encourage drivers to keep their eyes and vehicle in the driving lane when a shoulder is present.

Non-motorway rural roads are known to put drivers at risk of death or injury. In Europe, 55% of all road accident fatalities occurred on such road networks in 2015 (European Road Safety Observatory [ERSO], 2017). A large proportion of these road fatalities involved single-vehicle accidents (ERSO, 2015; Observatoire National Interministériel de la Sécurite Routière [ONISR], 2010, 2019), and most of them related to lane departures (see Najm et al., 2007). To combat the risk of single-vehicle accidents on rural roads, several experts have recommended installing paved shoulders adjacent to traffic lanes (Garber and Kassebaum, 2008; Organisation for Economic Co-operation and Development [OECD], 1999; Service d'Etudes sur les Transports, les Routes et leurs Aménagements [SETRA], 2002). This measure aims to provide drivers with a recovery area in cases of steering errors (Ogden, 1997), but it is also designed to accommodate cyclists and slow-moving vehicles (American Association of State Highway and Transportation Officials [AASHTO], 2011; Armour and McLean, 1983; Hall et al., 1998; SETRA, 2008). Roads both straight and curved that are equipped with paved shoulders have been proven to reduce accidents by about 30% for a wide range of traffic densities and shoulder widths (Armour and McLean, 1983; Zegeer et al., 1994; Elvik et al., 2009) in comparison to unequipped roads (e.g., Turner et al., 1981).

Researchers who have examined the influence of paved shoulders have reported beneficial effects in terms of lateral positioning on straight roads. Indeed, compared to a road without a shoulder, drivers shifted to the right[1] of their lane when in the presence of a 1.50 m shoulder (Bella, 2013). Other studies showed that as the width of the shoulder increased, drivers moved more and more to the right of their lane (Ben-Bassat and Shinar, 2011; Mecheri et al., 2017; see also Van Driel et al., 2004). These behavioural changes allow drivers to move away from oncoming traffic without getting closer to the edge of the road. Interestingly, while drivers gradually shifted to the edge line when the shoulder is enlarged, they systematically adjusted their lateral position to keep their vehicles within the lane boundaries and exhibited similar lateral-position variability across shoulder-width conditions (Mecheri et al., 2017). This suggests that while drivers use the width of their lane differently in the presence of a shoulder on straight roads, they may not see a shoulder as an extra driving lane but only as a recovery area.

In bends, it is well documented from real-world (e.g., Kandil et al., 2009) and simulator (e.g., Mars, 2008) studies that drivers cut corners.

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[1] The arguments are developed for countries with right-hand traffic lanes. Driving on the right side of the road implies that oncoming traffic is located on the left of the vehicle while the shoulder adjacent to the travel lane is located on the right of the vehicle.

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Corner-cutting consists of steering to the outer lane's edge before entering the curve and moving towards the inner-lane boundary around the apex (Boer, 1996). This strategy is used to reduce the curvature of the trajectory so that driving speed can be maintained. Corner cutting is very common in negotiating turns (Barendswaard et al., 2019). In fact, it has been shown that a path that cuts the corner is more likely to be attributed to a human driver, whereas driving in the centre of the lane is more readily associated with automated driving (Bazilinskyy et al., 2021). This type of trajectory likely contributes to run-off-road crashes occurring in bends, as lateral vehicle placement is considered one of the critical safety-related characteristics in negotiating bends (Steyer, 2000). In right-hand bends where the shoulder is installed on the inside of the curve, it has been observed that the presence of a shoulder increases corner-cutting. Bella (2013) found that drivers shifted 40 cm towards the inside of a sharp curve in the presence of a 1.50 m wide shoulder. Ben-Bassat and Shinar (2011) observed that lateral deviation towards the inner lane boundary increased substantially with shoulder width (35, 53 and 70 cm from the centre of the lane in 0.50, 1.20 and 3.00-m shoulder-width conditions, respectively). However, in left-hand bends, lateral positions were little affected by the presence of a shoulder. Although the results of these studies converge (Bella, 2013; Ben-Bassat and Shinar, 2011), both studies were conducted using an applied perspective regarding roadway design elements. One can hardly infer from these data why drivers steered closer to the edge line in right-hand bends equipped with a shoulder. This question deserves to be investigated to better understand drivers' behavioural adaptations to shoulders.

From a road-safety perspective, it is recognized that paved shoulders make bends more forgiving (Garber and Kassebaum, 2008; OECD, 1999; SETRA, 2002). In line with this, Ben-Bassat and Shinar (2011) demonstrated that drivers' perceived safety on undivided highways increased with the shoulder width and was higher on right-hand than left-hand bends regardless of shoulder width. One can assume that this greater sense of safety induces a change in drivers' perceptions of shoulders during right-curve negotiation in comparison to straight road sections; they may see the shoulder as a space that allows them to flatten out their path by cutting the corner to a greater extent. The differences in lateral deviation observed between shoulder conditions could then be the result of drivers planning their trajectories differently depending on whether a shoulder is present.

Since it has been robustly demonstrated that gaze and steering are tightly coupled in curve driving (Lappi and Mole, 2018), one way to determine whether drivers plan their trajectories differently in the presence of shoulders is to examine whether the visual control of steering is affected by a shoulder concomitantly to the steering trajectories in right curves. Several studies have indeed shown that when the gaze is manipulated so that it is laterally offset from the centre of the road, the trajectory tends to be deflected in the same direction. This has been observed in straight lines (Readinger et al., 2002) but also in bends with high (20 and 30°; Kountouriotis et al., 2015) or low (5–11°; Robertshaw and Wilkie, 2008; Kountouriotis et al., 2012) gaze eccentricity. Robertshaw and Wilkie (2008) found, however, that this effect is mainly valid for large lane widths (6 m). On narrow roads (3 m), lateral position error compensation mechanisms that are based on the peripheral view of lane edges come into play and limit this effect. Some studies have even found a trajectory shift in direction opposite to the deviation of the gaze (Mars, 2008; Crisler et al., 2009). Based on this literature, the hypothesis that installing or widening a shoulder affects drivers' gaze strategies in right-hand bends is a possible explanation for how shoulders affect drivers' behaviour. Specifically, in the presence of a shoulder, drivers may change the way they sample the road scene by directing their gaze more towards the inside of a curve (towards the shoulder) and, as a result, steer further inside. However, it is not known whether drivers' gaze strategies in right-hand bends are affected by the presence and width of shoulders.

The present study aims to examine drivers' visual strategies in relation to their steering trajectories in right-hand bends that are equipped with paved shoulders. For this purpose, drivers negotiated a series of bends on a simulated two-lane rural road with or without a shoulder while their gaze and steering behaviour were recorded. The widths of the shoulder (0, 0.75 and 1.25 m) and the lane (2.75 and 3.50 m) were manipulated. Based on previous findings, a series of hypotheses were formulated.

H1. Shoulder presence hypothesis: If the extra space provided by a shoulder is seen as an opportunity to straighten a trajectory, the presence of a shoulder would cause drivers to look further inside the curve and steer in the same direction as a result.

H2. Shoulder width hypothesis: Following Ben-Bassat and Shinar (2011), it was hypothesized that the wider the shoulder, the more the gaze and the trajectory would deviate towards the inside of a curve.

H3. Lane width hypothesis: On a narrow lane, the presence of a shoulder may induce a greater orientation of the gaze toward the inside of a curve, but steering trajectories could remain relatively unchanged. According to Robertshaw and Wilkie (2008), this would be due to the information provided by inner edge line that provides a stronger feedback for the compensation of lateral position errors.

1. Method

1.1. Participants

Eighteen participants aged between 23 and 50 years (mean age = 36 years; SD = 10 years; 9 females), all with normal or corrected vision, were recruited for this experiment via web advertisements. The experiment was approved by the ethics committee of Université Gustave Eiffel. The participants had been fully licensed for at least two years. No professional drivers were involved. The self-reported total mileage ranged from 22,000 to 490,000 km (mean = 229,611 km; SD = 205,480 km). All participants provided their informed consent to be included in the study and did not know about the purpose of the experiment.

1.2. Experimental setup

The experiment was carried out using a low-cost driving simulator (Fig. 1) that was equipped with a force-feedback steering wheel (Logitech G25). A virtual full-scale vehicle cab (vehicle width = 1.86 m, including mirrors) was displayed on the screen (Fig. 1), as it has been shown that providing a virtual full-scale cab increases the drivers' ability to adjust steering to the width of the lane in low-cost simulators (Mecheri and Lobjois, 2018). Images were displayed on three screens that were 1.22 m wide and 0.70 m high (60 Hz refresh rate; resolution of 3840 × 2160 pixels). The distance between the participant's head and the centre of each screen was 1.05 m, making the field of view 180° horizontally and 37° vertically. Three loudspeakers generated realistic engine and environmental noises. The data were collected at a sampling rate of 60 Hz.

Fig. 1. Illustration of the low-cost driving simulator with a virtual full-scale cab displayed in the visual scene.

The visual scene represented a two-lane rural road in a traffic-free environment with one lane going in each direction. The road surface was textured and marked by a discontinuous line 0.18 m wide on the edges and 0.15 m wide in the centre. The surrounding terrain was depicted as a flat rural landscape. The participants drove on the right side of the road.

A Pertech head-mounted monocular eye tracker was used to record the participants' eye movements at a sampling rate of 50 Hz. This monocular eye-tracker has 0.25° of accuracy (according to the manufacturer's specifications) and uses pupil-tracking technology with an image processing algorithm to define ocular direction. It was calibrated using a 7-point grid.

Data from the simulator, including the tangent point position in the coordinate system of the screen (in pixels), were sent to the eye-tracker software. Gaze positions were automatically calculated and expressed (in pixels) in the same coordinate system. The synchronisation between the two data sets was achieved through a Network Time Protocol server/client application.

1.3. Experimental design and task

Six experimental rural roads that corresponded to two lane widths (3.50 and 2.75 m) and three shoulder widths (0, 0.75 and 1.25 m) were used in this study (Fig. 2). The lane widths were selected from typical lane designs in France (see Hall et al., 1998; SETRA, 1994). The shoulder widths were determined using French regulations for shoulders on rural roads; 0.75 m and 1.25 m corresponded to the minimum and recommended widths, respectively.

On each experimental road, the participants had to perform a repetitive cornering task in a right-hand bend which had a radius and arc length of 200 m as measured from the centre of the road. At the beginning of each trial, the participants were positioned in the centre of their (straight) lane at 50 m from the bend entry and steered with an initial speed of 90 km/h (i.e., the legal speed limit for two-lane rural roads in France). Their speed was maintained constantly by the simulator software so that the trajectories in the bend were not influenced by any individual speed reduction strategies. Given the constant speed and road portion length (250 m), each experimental trial lasted 12 s.

1.4. Procedure

Upon their arrival, the participants filled out biographical and consent forms. They were then invited to sit down in the simulator and were encouraged to adjust the driving seat before the nature and requirements of the task were explained. They were told that they would have to drive repeatedly on a right-hand bend on a two-lane rural road while their driving speed would be kept constant. Participants were asked to drive as they would normally do with their own car on a two-lane rural road while obeying traffic rules. They were then informed that each trial would begin with a black screen, which would be replaced with the visual scene. At this point, they had to drive until they reached the end of the bend, at which point the black screen reappeared. The participants were then allowed to get used to the simulator by driving on a winding rural road that featured several different curves. Before performing the experimental trials, the participants carried out six practice trials to familiarize themselves with the experimental task. After that, they were equipped with the eye tracker, and the device was calibrated (this was done before each experimental session). During the experiment proper, the participants completed one block of eight successive trials on every experimental road; the order of presentation was random. The participants did not receive feedback on their driving performance. They took a short break every two roads, during which they were free to leave the simulator, if necessary. The experimental session lasted about 1 h.

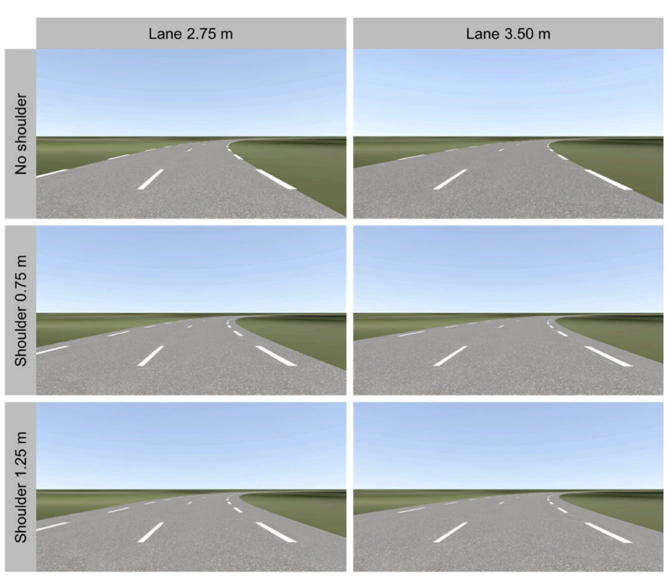

Fig. 2. Screenshots of the six experimental roads used in the experiment. The point of view is that of the participants at the beginning of the curve.

1.5. Data and statistical analysis

Driving measures. Driver behaviour was assessed in terms of lateral position in the lane. The lateral position was defined as the distance in centimetres between the centre of the participant's vehicle and the centre of his or her driving lane. To obtain a straightforward view of the trajectories taken by participants along the curve, we computed the lateral position at three points in the bend (Fig. 3A). LP_{Entry} corresponded to the instantaneous position in the lane at curve onset. LP_{Apex} indicated the instantaneous position in the lane when the driver reached half of the curve. LP_{Max} corresponded to the vehicle's closest position to the inside edge of a curve. Negative values indicated deviation toward the outside edge line, whereas positive values indicated deviation toward the inside edge line. Based on these variables, we also calculated the amplitude of corner-cutting as measured by the difference between LP_{Max} and LP_{Entry}. Finally, we computed the lane departure duration, which we defined as the percentage of the total time that the participant's vehicle was outside the lane. A departure began when any wheel touched the inner lane marking.

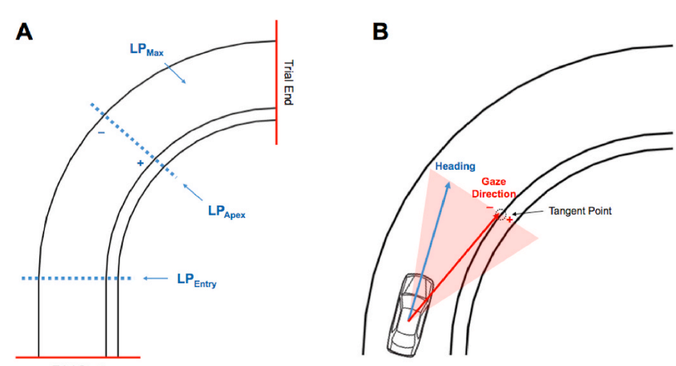

Fig. 3. Schematic representation of the dependent variables computation according to the geometry of a bend. (A) The first 50 m of each trial consisted of a straight road followed by a bend of 200 m. Three lateral-position variables were calculated: LP_{Entry} (position at 0 m into the curve), LP_{Apex} (position at 100 m into the curve), and LP_{Max} (innermost position). Lateral position was calculated relative to the lane centre, with positive values corresponding to a deviation toward the inside edge of the curve. (B) The gaze behaviour was analysed as the horizontal angular deviation from the tangent point. As an approximation, gaze deviation was considered to be either in the driving lane (negative angular deviations) or beyond the edge line (positive angular deviations).

Gaze measures. Given our hypothesis that drivers would look more towards the inside of a curve when in the presence of a shoulder, we examined gaze behaviour by computing the deviation of the gaze on the horizontal axis relative to the tangent point (TP; i.e., the point in the bend where the direction of the inside edge line seems to reverse from the driver's viewpoint, see Fig. 3B) (Kandil et al., 2009; Land and Lee, 1994; Wilson et al., 2007). The TP was used as a dynamic spatial reference to analyse visual strategies as it was found that gaze points in the vicinity of the TP capture a large proportion of guiding fixations regardless of whether they are future path fixations (e.g., Mars and Navarro, 2012; Robertshaw and Wilkie, 2008) or fixations to the TP itself (e.g., Kandil et al., 2009). As the TP was located on the edge line, this provided a straightforward view of gaze orientation as being either in the lane or beyond the edge line. In practical terms, the visual scene was divided into twenty intervals of 1° of angular deviation from the TP (from −10° to +10°), and the proportion of gaze points falling within each interval was computed for each bend (the straight-line approach has been excluded). Gaze points that fell beyond 10° of eccentricity were distributed between two additional classes (<-10° or >+10°).

These variables were analysed with repeated measure analyses of variance (ANOVAs). The effects of lane width and shoulder width on driving measures were assessed using 2 (lane width: 2.75, 3.50) × 3 (shoulder width: 0, 0.75, 1.25) ANOVAs. For gaze distribution, we performed a three-way ANOVA and used lane width, shoulder width and angular deviation from the TP as within-participant factors. All tests were done with p set at .05. Mauchly's test of sphericity was conducted to determine whether the sphericity assumption was violated. In cases of violation, the Greenhouse-Geisser correction was used and modified degrees of freedom were reported. To follow up on significant effects, Newman–Keuls post hoc tests were run when necessary. For each effect, partial eta-squared (η_p^2) was calculated to determine the proportion of total variability accounting for the effect. Descriptive statistics were reported using means and standard deviations (mean ± *SD*).

2. Results

2.1. Driving measures

The 2 × 3 repeated measures ANOVA on LP_{Entry} revealed only a main effect of shoulder width ($F_{1.44,\ 24.57} = 4.21$, $p = .03$, $\eta_p^2 = 0.20$). Under the no-shoulder condition, the drivers entered the bend with a mean deviation toward the outside edge (−4 ± 31 cm), whereas they drove more in the right half lane in presence of a shoulder (5 ± 28 and 6 ± 29 cm from the centre of the lane in the 0.75- and 1.25-m shoulder-width conditions, respectively).

Similarly, only a main effect of shoulder width was found for LP_{Apex} ($F_{1.34,22.88} = 5.71$, $p = .02$, $\eta_p^2 = 0.25$). Under the no-shoulder condition, the drivers maintained a middle-lane position on average (0 ± 30 cm). By contrast, a mean inward deviation was observed when a shoulder was present (9 ± 29 and 11 ± 34 cm from the centre of the lane in the 0.75- and 1.25-m shoulder-width conditions, respectively).

The ANOVA on LP_{Max} indicated a main effect of lane width ($F_{1,17} = 7.751$, $p = .01$, $\eta_p^2 = 0.31$) due to a smaller lateral deviation on the narrow lane (40 ± 26 and 48 ± 30 cm for the 2.75 and 3.50 m wide roads, respectively) and a main shoulder-width effect ($F_{1.43,24.31} = 12.19$, $p < .001$, $\eta_p^2 = 0.42$). A post hoc test for the shoulder effect revealed that the innermost lateral position in the bend was further down the inside edge line when a shoulder was present (34 ± 27, 48 ± 27 and 49 ± 28 cm in the 0, 0.75- and 1.25-m shoulder-width conditions, respectively). The effects of shoulder width on the lateral position at the three key points in the bend are depicted in Fig. 4.

The ANOVA performed on the amplitude of corner-cutting demonstrated only the main effect of lane width ($F_{1,17} = 11.07$, $p = .01$, $\eta_p^2 = 0.39$). The amplitude of corner cutting was significantly larger on a wide lane (46 ± 17 cm) than on a narrow lane (37 ± 13 cm).

Regarding the lane departure duration, the statistical analysis revealed the main effect of lane width ($F_{1,17} = 12.93$, $p < .01$, $\eta_p^2 = 0.44$) and the main effect of shoulder width ($F_{1.51,25.81} = 12.19$, $p = .03$, $\eta_p^2 = 0.21$). Participants spent more time off the lane on the narrow lane (7 ± 10%) than on the wide lane (2 ± 6%) and in presence of a shoulder (5 ± 8 and 6 ± 12% in the 0.75 and 1.25 m conditions, respectively) than in the absence of one (2 ± 4%).

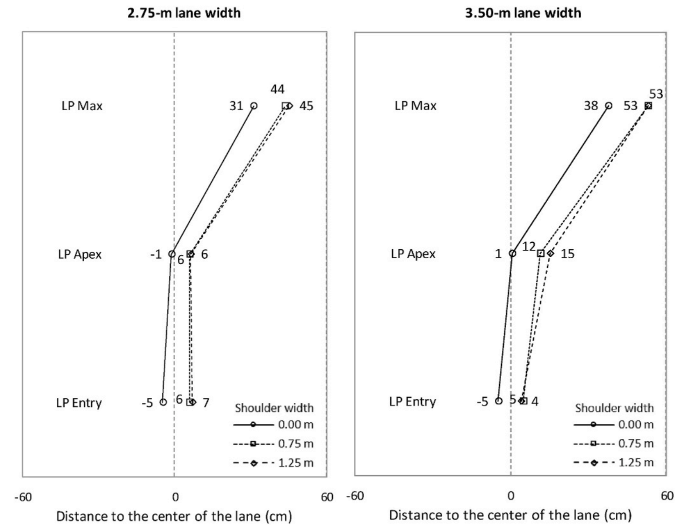

Fig. 4. Lateral position at the three measurement points in the bend (the entry, the apex and the innermost position) as a function of lane width and shoulder width. Zero represents the centre of the lane.

2.2. Gaze measures

The 2 × 3 x 22 repeated measures ANOVA on the proportion of gaze points revealed the main effect of angular deviation ($F_{21,294} = 24.33$, $p < .001$, $\eta_p^2 = 0.63$) and a significant interaction between shoulder width and angular deviation ($F_{42,588} = 2.28$, $p < .001$, $\eta_p^2 = 0.14$). Most visual sampling was concentrated in the vicinity of the TP (85% between −3° and 3°), with almost two-thirds of these gaze points that were oriented towards the lane (i.e., from −3° to 0°). The peak of the distribution (23%) occurred at the [−1°; 0°[interval.

The post hoc test for the interaction between shoulder width and angular deviation revealed that this overall distribution of gaze differed as a function of shoulder width with a larger proportion of gaze points

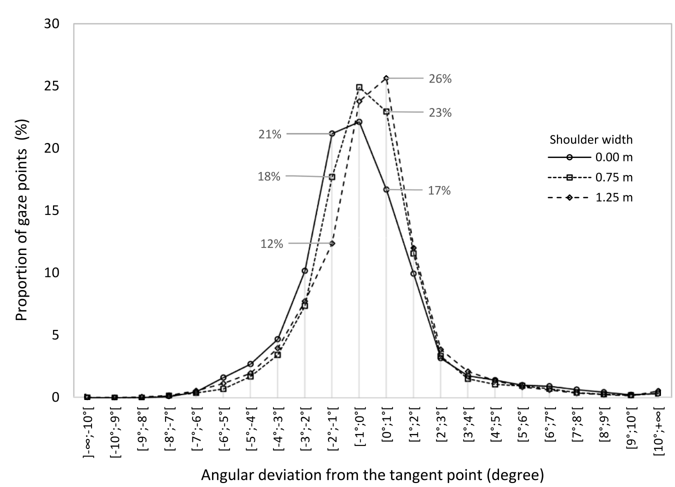

Fig. 5. The proportion of the gaze points (%) as a function of shoulder width and angular deviation from the tangent point on the horizontal axis (degree). Negative angular deviations indicate that drivers' gaze is directed toward the lane.

directed beyond the TP in the presence of a shoulder (Fig. 5). A higher proportion of gaze points falling within the [−2°; −1°[interval was found in the no-shoulder condition than in the two shoulder conditions, which also differed between each other. Conversely, a higher proportion of gaze points was observed within the [0°; 1°[interval in the presence of a shoulder, regardless of its width, compared with the no-shoulder condition.

3. Discussion

The objective of this study was to examine whether the presence of a shoulder influences the distribution of a drivers' visual strategies in relation to their trajectories in right-hand bends. For this purpose, the participants repeated a cornering task on a simulated two-lane rural road with or without a paved shoulder while their free gaze and steering strategies were recorded. Gaze behaviour was analysed as the horizontal angular deviation of gaze points from the TP. This made it possible to characterize the gaze as being oriented either towards the lane or towards the shoulder. Three hypotheses were formulated as follows: H1. Drivers may look further inside the curve and steer in the same direction when a shoulder is present; H2. The gaze and the trajectory may deviate more towards the inside of a curve when the shoulder is widened; H3. When it is installed on a narrow lane, the shoulder may induce changes in gaze but not in steering due to a stronger edge-line feedback that comes into play.

Gaze and driving measures revealed significant effects of the shoulder on driver behaviour in right-hand bends. Under the no-shoulder condition, significantly more gaze points were directed in the interval [−2°; −1°[in comparison to the shoulder conditions. The drivers thus looked more within the lane boundaries and steered accordingly at a significantly smaller distance from the centre of their lane and with significantly lower lane departure duration. It is worth noting that a similar pattern of gaze distribution and steering trajectories was found in prior curve-driving studies that used a similar method (Mars and Navarro, 2012; Schnebelen et al., 2019). In the presence of a shoulder, the participants gazed more at the interval [0°; 1°[. As a result, they steered further towards the inside of the curve, in accordance with previous studies (Bella, 2013; Ben-Bassat and Shinar, 2011). Consequently, the trajectories taken by the participants were not always well-suited to the manoeuvring space as more time was spent off the lane. This pattern of results supports the hypothesis H1 that the shoulder is seen by drivers as an opportunity to increase corner cutting and has an influence on path planning. Although the drivers steered closer to the edge line, the results revealed that the amplitude of corner-cutting was not affected by the presence of a shoulder. The drivers adopted roughly equivalent path curvatures in the three shoulder width conditions, but the presence of a shoulder led to a rightward shift of the trajectory, which was observed at the three measurement points. This suggests that the tight coupling between gaze and steering control in bends is preserved when a shoulder is added, but the driver's path planning is changed.

The fact that the drivers used the extra space provided by the shoulder is consistent with Ben-Bassat and Shinar's results (2011). In accordance with the "steer where you look" strategy whereby drivers look at successive waypoints (Lappi and Mole, 2018; Wann and Swapp, 2000; Wilkie and Wann, 2003), the participants in the present study looked more or less towards the inside of the curve depending on the presence or absence of a shoulder. Nevertheless, based on this visual strategy and the increased feeling of safety, one might have expected that the wider the shoulder, the more the gaze and the trajectory would deviate towards the inside of the curve. This was not observed. Contrary to the hypothesis H2, the effects of the shoulder on gaze and steering behaviour did not depend on shoulder width, which operated in an all-or-nothing mode. The functional significance of this observation may be found in the hypothesis formulated by Mars and Navarro (2012). These authors assumed that drivers' gaze is not directed towards points on the future path but rather to a safety line that they do not want to cross. According to this perspective, maintaining some distance from the inside edge line under the no-shoulder condition makes sense since drivers cannot risk losing control of their vehicles by driving on the side of the road. In contrast, the presence of a shoulder could increase the acceptable trajectory envelope, which would explain why drivers gazed more beyond the TP and why they spent more time off the lane. However, when the width of a shoulder increases, drivers limit this behaviour because they know the shoulder is not a drivable area.

From a more theoretical point of view, these findings can be comprehensively accounted for by the concept of field of safe travel (Gibson and Crooks, 1938). The boundaries of the field of safe travel are determined by objects or features of the terrain that have a negative 'valence' from the driver's viewpoint, such as obstacles or low-grip surfaces. According to Gibson and Crooks (1938), a positive or negative valence refers to the propensity of an object to induce a movement towards or away from it. In the present case, the inner edge line, which coincided with the road edge in the absence of a shoulder, was equated to an obstacle. In the presence of a shoulder, the inner edge line may take on a less negative valence and no longer be considered as an obstacle as the shoulder opens a new field of safe travel that did not exist before. In this case, the inner edge line is no longer a reliable indicator of the objective possibilities of locomotion and becomes a purely legal limit. From the driver's point of view, this may lead to a compromise between the legal interdiction of crossing the edge line and the possibility of extending the field of safe and efficient travel. As stated by Gibson and Crooks (1938), the possibilities for opening up a new field of safe travel depend on a driver's sensitivity to the pertinence of this field for locomotion and upon the degree to which this field is imbued with meaning for locomotion. In the present study, one can assume that drivers considered driving on the shoulder to be pertinent insofar as only 3 participants out of 18 did not encroach into this road space. However, they seemed to have made some kind of compromise with the meaning of such behaviour that contravened the traffic rules to keep this behaviour within a satisfying limit.

The present results also revealed that the shoulder effects on the driving behaviour were similar between the two lane-width conditions. Although the lane departure duration was higher with a shoulder than without – and the amplitude of corner-cutting was similar – these shoulder-related effects did not vary with the width of the lane. This goes against the hypothesis H3 that was based on the results of Robertshaw and Wilkie (2008). Indeed, if the compensation of lateral deviations were stronger in narrow lanes, then the shoulder effect on the lane departure duration would have been mitigated. This discrepancy between studies may be due to the fact that the participants drove freely and did not have to keep their vehicles as close to the centre of the lane as possible, a condition in which the influence of the edge lines in compensatory control may play a more determining role (e.g., Kountouriotis et al., 2012). These results reinforce the idea that shoulder effects are the result of different trajectory planning and further suggest that creating or widening a shoulder can be done equally well on wide and narrow rural roads without increasing the amplitude of corner-cutting.

These results lead us to consider road layout that would prompt drivers to keep their vehicles in the lane in right-hand bends equipped with shoulders. The objective would be to preserve the safety benefits of the shoulder without inducing deleterious changes in the trajectory (e.g., encroachment on the shoulder or reduction of the lateral clearance while overtaking cyclists riding on the shoulder). Since the present results demonstrated that drivers' trajectory follows their gaze, the objective would also be to prevent drivers from shifting their gaze towards the shoulder. One method would consist of implementing perceptual countermeasures such as a continuous, wider or double edge line (e.g., Charlton, 2007), peripheral transverse bars (e.g., Calvi et al., 2019) or herringbones (e.g., Charlton, 2007; Awan et al., 2019). Such delineation devices would be aimed at strengthening guidance signals dedicated to trajectory planning and/or inducing a negative valence from the driver's viewpoint. In the studies of Bella (2013) and Ben-Bassat and Shinar (2011), experimental roads had continuous edge lines. Since the drivers still deviated to the inside of the bend in the presence of a shoulder, it can thus be assumed that implementing continuous lateral marking is not effective in counteracting the influence of the shoulder on gaze and steering behaviour. Out of all the countermeasures that have been tested to make bends safer, herringbones have a good potential to influence lateral positions around bends with shoulders. Indeed, drivers were found to move further towards the outer part of their lane at curve entry (Charlton, 2007; Awan et al., 2019) and to maintain a more central position in the bend (Awan et al., 2019, but see Ariën et al., 2017) in the presence of herringbones in comparison to a control condition without altering corner-cutting behaviour. Additionally, this pavement treatment could be coupled with advanced warning signs that are known to reduce speed (Charlton, 2007) insofar as corner-cutting and time spent out of the lane are reduced at a slower speed (Raw et al., 2012; Xu et al., 2018).

It warrants mentioning that the choice was made to hold drivers' speed constant in this study, preventing the ability of drivers to modulate their speed to negotiate bends. This method is commonly used in studies investigating the relationship between gaze and steering control (e.g., Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008; Schnebelen et al., 2019), as it facilitates comparison between experimental conditions. However, it limits the ecological validity of the study. Therefore, it would be relevant to replicate this experiment with participants driving at a self-determined speed and to extend the analysis to curves of various radii in order to generalize the findings of this study.

In conclusion, this study showed in accordance with previous research that drivers steer further inside right-hand bends with the presence of a shoulder, and that this was observed at three points in the curve. Although the amplitude of corner-cutting was not affected by the presence of a shoulder, the increases in lateral deviation resulted in more time spent out of the lane. Importantly, the analysis of visual strategies provided compelling evidence that this driving behaviour is due to a modification of the visual sampling of the road ahead. In the presence of a shoulder, the drivers' gaze deviated towards the inside of the curve, and the steering trajectories followed, regardless of the shoulder width. This alteration of behaviour can be viewed as the product of the drivers' sensitivity to the shoulder as a new field of safe travel (Gibson and Crooks, 1938) that induces a compromise, from the driver's point of view, between the legal interdiction of crossing the edge line and the possibility of steering more efficiently (shorter path length through the curve). Based on our findings, it would be worth examining the effects of delineation treatments to better define travel paths on roads that are equipped with shoulders in order to bring the drivers' gaze and vehicle back to the lane. As shoulders are also suitable for cycle use, another valuable future direction might be to examine drivers' steering trajectories when overtaking cyclists in right-hand bends.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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