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Effects of visual roll on steering control and gaze behavior in a motorcycle simulator

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ABSTRACT

The goal of this study was to examine the effects of visual roll tilt on gaze and riding behavior when negotiating a bend using a motorcycle simulator. To this end, experienced motorcyclists rode along a track with a series of right and left turns whilst the degree of visual roll tilt was manipulated in three different conditions. Gaze behavior was analyzed by using the tangent point as a dynamic spatial reference; the deviation of gaze to this particular point was computed in both the horizontal and vertical directions. Steering control was assessed in terms of the lateral positioning, steering stability and number of lane departures. In the no-roll condition, the motorcyclists tracked a steering point on the road ahead, which was compatible with the hypothesis of "steer where you look" behavior. In the roll condition, our results revealed that the horizontal distribution of gaze points relative to the tangent point was preserved. However, significantly more fixations were made further ahead of the tangent point in the vertical direction. This modification of visual behavior was coupled with a degradation in steering stability and an offset in lateral positioning, which sometimes led to lane departures. These results are discussed with regard to models of visual control of steering for bend negotiation.

1. Introduction

Current statistics show that the total number of road deaths is falling in European countries. However, the proportion of motorcycle rider fatalities is increasing. The risk of motorcyclists being killed on the road is 24 times higher than that of car drivers for the same number of kilometers driven (ONISR, 2007). This makes motorcycle safety an important research area. Yet, behavioral studies of motorcyclists are scarce. Until recently, this could be explained by the lack of reliable tools for studying motorcyclists' behavior in relevant conditions and situations (Espié, Boubezoul, Aupetit, & Bouaziz, 2013). The development of driving simulators has made it possible to now address many of the challenges that face the traffic safety community; thus, riding simulator studies have become increasingly popular. In particular, they have been used to study rider behavior when taking a bend (Crundall, Crundall, & Stedmon, 2012), when approaching an intersection (Crundall,

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Stedmon, Saikayasit, & Crundall, 2013) or to perceive hazards (Hosking, Liu, & Bayly, 2010; Liu, Hosking, & Lenné, 2009). They have also been used to detect risky rider behavior (Di Stasi et al., 2009), train riders' cognitive abilities (Di Stasi, Contreras, Cándido, Cañas, & Catena, 2011) and to test the reliability of assistance systems (Huth, Biral, Martín, & Lot, 2012).

Although the amount of research that focuses on rider behavior is growing, few studies have dealt with motorcycle simulator fidelity. Next to nothing is known about motion cueing and self-motion perception in riding simulation because of a lack of motorcycle simulator studies that seek to select a proper motion cueing algorithm (for a recent review of the existing interactive riding simulators, see Benedetto et al., 2014). However, various studies have argued for the introduction of visual roll (where the scenery is tilted in the opposite direction to the bend; see Fig. 1) to mirror the riding experience of leaning into bends.

In a 3 DOF motorcycle simulator with a visual display of $150° \times 35°$, Kageyama and Tagami (2002) examined the effects of motorcycle mock-up and visual roll motion on the riders' subjective experience of leaning into bends. The authors showed that the sensation of leaning was improved when the inertially-specified roll motion was coupled with tilting scenery. Using some of the most advanced dynamic motorcycle simulators (5DOF, visual field of view higher than $180° \times 60°$), Cossalter, Lot, and Rota (2010) and Shahar, Dagonneau, Caro, Israël, and Lobjois (2014) showed that the most realistic riding experience was reported when the roll of the visual scene was larger than that of the motorcycle mock-up. Using a fixed-base riding simulator with a visual angle of $72° \times 62°$, Stedmon et al. (2011) compared conditions in which the visual horizon was rolled in the opposite direction to the bend with conditions where the horizon remained stationary (i.e., no roll motion). Both conditions resulted in similar riding performance; however, this manipulation had an effect at a subjective level. Specifically, most of the riders (10 of 16) preferred the configuration where the horizon was rolled, two preferred the constant horizon condition, while four participants had no preference.

To date, scene tilting in riding simulation has largely been used to support the experience of leaning. Indeed, several studies have argued for the implementation of visual roll tilt to compensate for the physical workspace of motion-based motorcycle simulators, which is necessarily limited to avoid the sensation of falling off the simulator (Shahar et al., 2014). Visual roll tilt induces the experience of leaning when the motorcycle mock-up is static (Stedmon et al., 2011); this feeling is enhanced when the visual roll tilt is coupled to a physical one (Cossalter et al., 2010; Shahar et al., 2014). Additionally, according to Stedmon et al. (2011), it contributes to the physical fidelity of the simulator, i.e., the extent to which the simulation device replicates the real-world environment. Rolling the visual scene in the opposite direction to the movement of the motorcycle cab does, indeed, seem to comply with geometric principles as the ground gets visually closer to the riders when leant over.

However, in some respects, tilting the visual scene can also be seen as disadvantageous. First, recent results have shown that participants who prefer a large visual roll angle also exhibit greater symptoms of sickness than those who prefer a limited degree of visually induced leaning (Lobjois, Dagonneau, & Isableu, accepted for publication). Second, the introduction of a visual roll angle changes the natural dynamics of the scene. While the relative positions of the visual features of the scene are preserved, their absolute position in space, i.e., relative to the static rider, is determined by the amount of visual roll tilt. For instance, a visual target that moves horizontally in a condition in which there is no roll motion would have an additional vertical motion if roll motion was to be added (for an illustration, see Fig. 1). In order to track this target, the rider's oculomotor behavior would have to be modified; this may, in turn, influence steering control, which relies heavily on visual information.

It is well known that, when taking bends, drivers track particular points on the road to gather visual information, which is fed into the motor system in charge of steering control (e.g., Land & Lee, 1994; Mars, 2008; Wann & Swapp, 2000; Wilkie, Kountouriotis, Merat, & Wann, 2010). So-called two-level control models represent two distinct visual processes that determine the on-line visual control of steering (Donges, 1978; Mars, Saleh, Chevrel, Claveau, & Lafay, 2011; Salvucci & Gray, 2004). Compensatory corrections of a vehicle's lateral deviation from the intended path presumably rely on peripheral vision that encompasses the edge lines relatively close to the vehicle (Summala, Nieminen, & Punto, 1996). More distant visual information is acquired by guiding fixations, which then feed anticipatory control (Frissen & Mars, 2014; Land & Horwood, 1995). Recently, it has been proposed that fixations that are even more anticipatory, called look-ahead fixations, are a way of bringing about advance path planning and hazard detection (Lehtonen, Lappi, Koirikivi, & Summala, 2014; Lehtonen, Lappi, Kotkanen, & Summala, 2013; Mars & Navarro, 2012).

The exact nature of the visual cues targeted by guiding fixations has been a matter of debate. The tangent point, that is to say the point where the direction of the inside edge line seems to reverse from the driver's viewpoint (Kandil, Rotter, & Lappe, 2009; Land & Lee, 1994; Wilson, Stephenson, Chattington, & Marple-Horvat, 2007), has been proposed to be tracked in the visual scene in order to assess the road curvature at the sensorimotor level. An alternative hypothesis states that drivers look at the points on the road through which they wish to pass (Wann & Swapp, 2000; Wilkie & Wann, 2003); these points happen to fall close to the tangent point. Recently, Mars and Navarro (2012) proposed that drivers search for a safety line that delimits an acceptable trajectory envelope near the tangent point. Thus, even though the tangent point may not be fixated exactly, a large part of the guiding fixations fall in the area surrounding it. As such, it may be considered a useful dynamic spatial reference when analyzing drivers' gaze strategies. In the context of motorcycling, only two studies have investigated riders' visual strategies. These studies have mainly addressed and compared the visual scanning behavior of experienced drivers and motorcyclists. They have not, however, concerned themselves with the visual cues used by riders to guide steering (Nagayama, Morita, Miura, Watanabem, & Murakami, 1980; Tofield & Wann, 2001).

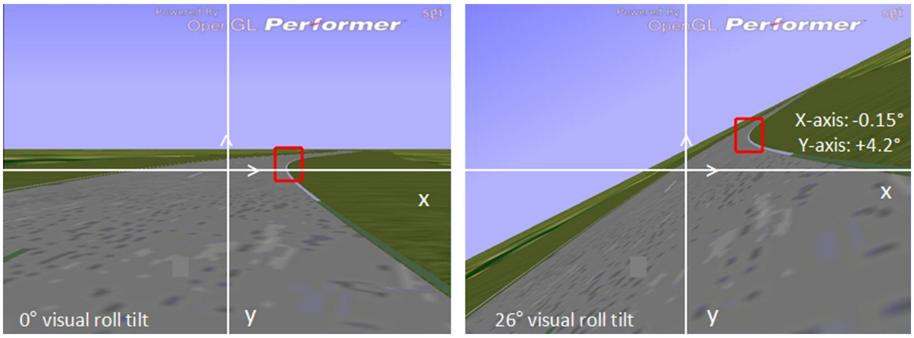

Fig. 1. Visual scene when negotiating a bend using a motorcycle simulator with non-tilting scenery (left panel) or tilting scenery of 26° (right panel). The red square illustrates a 3 × 3° tangent point area. In the right panel, i.e., when the visual scene is tilted by 26°, the tangent point moves −0.15° in the horizontal direction and 4.2° in the vertical one when compared with the left panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

With the introduction of visual roll tilt in riding simulation it is reasonable to think that the coordinates of the tangent point in the visual output would change and the consequences of this manipulation would be mainly seen in the vertical direction (see Fig. 1). If riding a motorcycle relies on a tight coupling between gaze and steering actions, then riding behavior may be impacted by scene tilting. Thus, the question that arises is whether or not ocular behavior and steering control are influenced by visual scene tilting.

Based on these considerations, the goal of the present study was to examine the effects of visual roll tilt on gaze and riding behavior when negotiating a bend using a motorcycle simulator. To this end, experienced motorcyclists rode along a track with a series of right and left turns whilst the amount of visual roll tilt was manipulated (no roll motion, and roll motion at low and high amplitudes). To investigate the effects of roll tilt on riders' visual control of steering, the tangent point was used as an objective reference point in the visual scene. The distribution of gaze direction relative to this particular point and steering parameters accounting for the control of the vehicle were analyzed. In addition, the effects of visual roll tilt on sickness symptoms were assessed.

2. Method

2.1. Participants

Twelve participants were recruited through advertisements on motorcyclists' forums and associations, and the web page of a motorcycle newspaper. To be recruited, participants were required to have held a motorcycle license for at least one year and to ride a minimum of 5000 km in a year. All participants had normal or corrected-to-normal vision, and were naïve as to the aims and expected outcomes of the experiment. The present study was approved by the IFSTTAR Ethics Committee and a compensation payment of 40 € for each person was agreed. Selected demographic information is provided in Table 1.

2.2. Experimental setup

2.2.1. Motorcycle riding simulator

The experiment was conducted on the IFSTTAR powered motion-based motorcycle simulator, which was used in its static mode throughout the experiment. The simulator comprised a motion platform, image-generation software, projection

Table 1
Selected demographic variables.

	Mean	Standard deviation	Range
Age (year)	35	12	23–56
Driving license (year)	16	11	3–36
Driving license (km/year)	12,916	12,738	1000–45,000
Motorcycle license (year)	14	12	2–36
Motorcycle license (km/year)	14,250	7021	5000–30,000
Time spent riding (h/week)	14	13	5–50
Type of road (%)			
Urban	36	21	5–70
Peri-urban	42	23	0–70
Rural	22	19	0–70

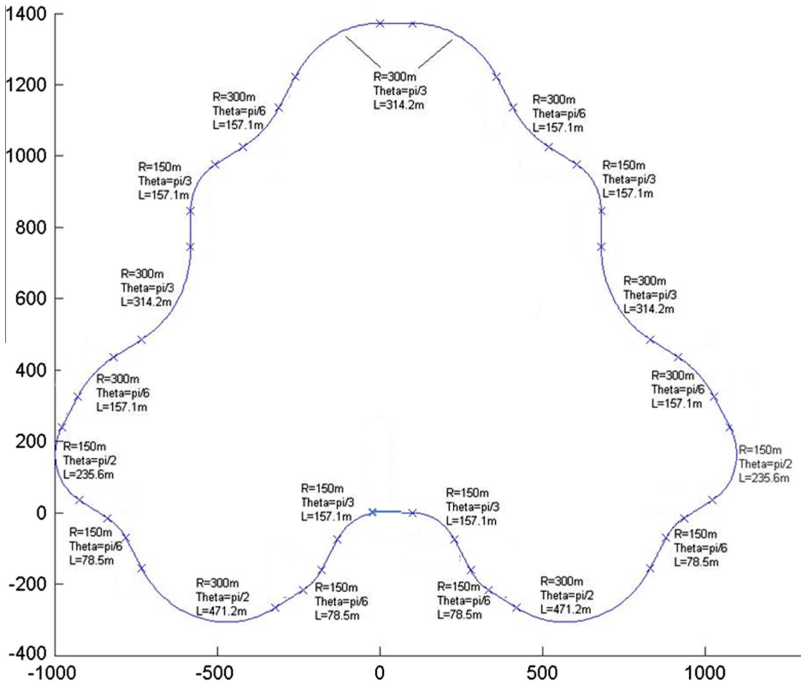

Fig. 2. Illustration of the track geometry and specifications for the features of each bend.

screen, and a sound system. It consisted of a standard motorcycle frame (125 cc) equipped with all the necessary parts, including a steering column with handlebars, gas tank, seat, footrests, throttle, front and rear brakes, and gear shifting devices. Steering feedback was refreshed at a frequency of 100 Hz. The simulator conception, design and functioning was fully described in Arioui, Nehaoua, Hima, Séguy, and Espié (2010) and Benedetto et al. (2014).

The simulated scene was displayed onto a white screen that was 185 cm wide × 124 cm high, subtending a visual angle of 60 × 40°. Participants faced the screen at a distance of approximately 165 cm when seated on the simulator. The images (refreshed at 30 Hz) were calculated and projected at the participant's eye height, and the simulated viewing angle was aimed at the vanishing point of the simulated scenario. Simulated engine sounds were provided by using a 4.1 speaker system.

The fully textured visual scene represented a single carriageway on a winding road with standard white lane markings in a traffic-free rural environment. The road was lined with trees and the width of each lane was 3.5 m. The whole track (Fig. 2) covered a total distance of 6.240 km. It consisted of 12 left and 8 right bends that were separated by a 100 m section of long straight road. Bend curvature was either 150 m or 300 m. Details of each bend are presented in Fig. 2.

2.2.2. Eye tracker

A Pertech head-mounted monocular eye tracker was used to record participants' ocular behavior with a sampling rate of 50 Hz. This device, based on the principle of a pair of glasses (without lenses), has 0.25° of accuracy and uses pupil-tracking technology with an image processing algorithm to define the ocular direction. A seven-point calibration was performed for each participant at the beginning of each experimental trial. Room lighting was kept constant during all the experimental trials.

The eye tracker and the simulator were synchronized and the communication between the two devices was established so that data about the 3D world (e.g., the tangent point position) and riding behavior were sent to the eye tracker software. This enabled us to automatically analyze gaze directions relative to the visual features of the scene and any riding measures.

2.3. Experimental design and task

We used a within-subjects design with three visual gains: Gain 0, which corresponds to the no-rolling condition; Gain 0.2, the condition in which visual roll tilt reproduces 20% of the leaning angle of a real motorcycle with similar speeds and curvature conditions; and Gain 0.4, which corresponds to the rendering of 40% of the leaning angle of a real motorcycle. These gains were implemented in the visual rendering model. Just as a real motorcycle's leaning angle depends on the passing speed and the path curvature, the magnitude of the visual roll angle in our setup was dependent on the speed of the virtual motorcycle and the curvature of its path, which was calculated for each bend using the rendering model. Hence, for a given curvature, the visual roll angle increased with speed. Similarly, for a given speed, larger curvatures, i.e., tighter curves, led to more extreme tilting angles of the visual scene. As the visual roll angle depended on individual riding behavior and strategy in the negotiation of the bends, it was recorded throughout the experiment for later inspection.

Participants were asked to perform the task as if they were riding for real and to observe speed limits (100 km/h). They were told that they could freely negotiate the bends and position themselves within in their lane, but were explicitly asked to keep the vehicle within the lane boundaries.

2.4. Procedure

After an explanation of the basic principle of the experiment, participants signed the informed consent form and demographic data were collected. The participants underwent a training session which consisted of two separate laps of the track. During this training session, the visual gain was 0.1 or 0.3 and the order of presentation was counterbalanced across participants. These two runs were also used to familiarize the participants with the speed limit. Verbal feedback about speed was given to the participants during the training session, so that they learned to maintain their speed inside reasonable limits. However, no speed feedback was given during data collection to avoid too much gaze direction toward the speedometer, which may have interfered with the primary goal of the study, i.e. investigating the influence of visual roll motion on steering control and gaze strategies. After the training session, participants were equipped with the eye tracker and the device was calibrated. The experiment proper consisted of three riding sessions, which corresponded to the three visual gains. For each riding session, participants rode two consecutive laps of the track, negotiating a total of 40 bends. The order of presentation of the gain conditions was counterbalanced across participants.

Participants also completed the Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993). The SSQ was first completed by the participants on arrival to obtain a baseline measure and then before and after each riding session. At the end of the experiment, participants were asked to evaluate the three riding sessions and to give their preference in terms of perceived visual comfort. The whole experiment lasted approximately 1 h 30 min.

2.5. Data analysis

Data analysis was limited to the bends, because the visual roll angle was expected to mainly vary during their negotiation. We then excluded from the analysis data from straight sections of road. As the position of the tangent point is computed on the basis of the instantaneous lateral position of the motorcycle in the lane, data from lane departure episodes also had to be excluded.

Some of the selected dependent variables were expressed as a distance in degrees relative to a particular point in the visual output. Consequently, the signs of measurements for the left and right bends differed on the horizontal axis. The signs of measurements obtained in left bends were then changed so that a negative value represented a deviation of position towards the left relative to the reference point (e.g., toward the road centerline if the gaze direction is expressed in relation to the tangent point position). In this way, a positive value represented a deviation of position in the opposite direction (e.g., deviation of gaze in the direction of the bend exit), regardless of the direction of the bend.

2.5.1. Effect of the visual gain on the dynamics of the scene and the tangent point

Visual roll motion depends on the riding behavior in each bend; thus, the magnitude of the visual roll angle and the position of the tangent point relative to the center of the image were calculated to get a clear view of the effect of the visual gain on the dynamics of the visual scene. For visual roll motion, the mean and the highest roll angle were computed for each participant in each bend. For the tangent point, the mean position relative to the center of the image was calculated on the horizontal and vertical axes. The minimum and maximum distances of the tangent point to the image center on both axes were also computed to account for the motion range of the tangent point.

2.5.2. Gaze behavior

The mean gaze position relative to the center of the image was first computed on both axes to determine whether the average gaze direction changes as a function of the visual gain. Ocular behavior dedicated to the picking up of visual information to guide steering was then addressed by determining the deviation of gaze relative to the tangent point. The mean deviation of gaze from this reference point was thus calculated as a global indicator of gaze positioning. To further understand gaze behavior, the visual scene was divided into 20 intervals of 1° of angular deviation from the tangent point and we computed the proportion of gaze points in each interval. Gaze points that deviated more than 10° in one direction or another were collapsed into two additional extreme classes (i.e., $<-10°$ or $>10°$). These data were computed on the horizontal and the vertical axes.

2.5.3. Riding behavior

The mean speed and lateral deviation from the centerline, as well as the standard deviation of lateral position and the number of lane departures, were calculated for each participant in each bend.

2.5.4. SSQ

The SSQ consisted of a checklist of 16 symptoms rated in terms of degree of severity (none, slight, moderate, severe). A weighted scoring procedure was used to obtain the total score to reflect overall symptoms of sickness, the highest possible score being 300. The SSQ also provided scores on three subscales (nausea, oculomotor disturbance, and disorientation). Total scores and subscale scores were calculated for each participant and each experimental condition.

These variables were input into repeated measures analyses of variance (ANOVAs) with the visual gain as a within-participant factor. The significance level was set at 0.05 for all statistical analyses. The effect size (η^2) was also computed. Significant effects were further examined using the Newman–Keuls post hoc test when necessary.

3. Results

3.1. Magnitude of the visual roll angle

As there was no visual roll in the Gain 0 condition, a paired t-test was used to compare the mean visual roll angle in the 0.2 and 0.4 gain conditions. The difference between gain 0.2 and gain 0.4 was significant ($t(11) = 17.59$, $p < .0001$), the visual roll angle increasing with the visual gain. A similar analysis was carried out on the maximum visual roll angle, revealing similar significant differences ($t(11) > 18$, $p < .0001$). The data are presented in Table 2.

3.2. Tangent point position in the visual output

The repeated measures ANOVAs (three visual gains) on the mean and extreme positions of the tangent point relative to the image center on the horizontal axis did not reveal any significant effect of the visual gain (Table 2).

For the vertical axis, the ANOVA revealed a significant effect of the visual gain on the mean ($F(2,22) = 20.64$, $p < .0001$, $\eta^2 = .65$) and the upper position of the tangent point relative to the image center ($F(2,22) = 85.07$, $p <. 0001$, $\eta^2 = .89$). Post hoc tests showed significant differences between the three gain conditions (Table 2). These results confirm that the visual roll mainly influenced the coordinates of the tangent point in the vertical dimension of the visual scene.

3.3. Gaze behavior

The ANOVA performed on the mean gaze position relative to the image center revealed a significant effect of the visual gain on the horizontal ($F(2,22) = 5{,}49$, $p < .05$, $\eta^2 = .33$) and vertical axes ($F(2,22) = 12{,}51$, $p < .001$, $\eta^2 = .53$). On the horizontal axis, the distance to the image center significantly decreased in the roll conditions in comparison with the no-roll condition (Table 2). With visual roll motion, the gaze position was not as far inside the curve. On the vertical axis, when the visual gain increased, the gaze position moved further away from the image center. The highest gain condition significantly differed from the two other conditions (Table 2).

Table 2
Effects of the visual gain on the mean and extreme visual roll angle (SD), the mean and extreme tangent point position in the visual output (SD) and the mean gaze position relative to the image center and to the tangent point (SD) on the horizontal and vertical axes.

	Gain 0	Gain 0.2	Gain 0.4
Visual roll angle (°)			
Mean	0.0 (–)	4.06 (1.3)	8.57 (2.6)
Max	0.0 (–)	5.11 (1.6)	10.81 (3.1)
Tangent point position relative to the image center (°)			
Horizontal axis			
Mean	5.90 (0.7)	5.85 (0.5)	5.91 (0.5)
Min	4.38 (0.8)	4.27 (0.8)	4.33 (0.7)
Max	7.42 (0.7)	7.47 (0.6)	7.62 (0.5)
Vertical axis			
Mean	−0.62 (0.4)	−0.35 (0.3)	−0.13 (0.5)
Min	−2.11 (1.0)	−2.21 (1.0)	−2.70 (1.8)
Max	0.24 (0.2)	0.69 (0.2)	1.16 (0.2)
Gaze position relative to the image center (°)			
Horizontal axis	9.22 (1.54)	8.55 (1.58)	8.79 (1.63)
Vertical axis	1.18 (0.54)	1.60 (0.97)	2.35 (1.02)
Gaze deviation from the tangent point (°)			
Horizontal axis	3.32 (1.24)	2.70 (1.35)	2.88 (1.38)
Vertical axis	1.80 (0.69)	1.94 (0.88)	2.49 (0.96)

Our results did not show any effect of the visual gain on the mean deviation of gaze from the tangent point in the horizontal direction (Table 2). When the visual scene was divided into 22 intervals of angular deviation from the tangent point on the horizontal axis, the ANOVA (3 visual gains × 22 angular deviations) performed on the proportion of gaze points showed a non-significant main effect of the experimental condition, a significant effect of angular deviation from the tangent point ($F(21,231) = 36.61$, $p < .0001$, $\eta^2 = .77$) and a non-significant interaction between both variables. The distribution of gaze points according to the visual gain and the horizontal angular deviation from the tangent point is depicted in Fig. 3. It can be observed that many fixations were made in the vicinity of the tangent point, but that they were shifted in the direction of the bend exit, with a peak of the distribution deviated from the tangent point by 2° of visual angle. A post hoc test on the effect of angular deviation confirmed this observation and the asymmetry of the distribution. The proportion of gaze points was significantly higher for angular deviations between 0° and 3° around the tangent point than all other intervals (all *ps* < .01). When comparing the concentration of gaze points on each side of the tangent point, many more fixations were directed toward the bend exit (81.25% for the [0°,>10°] interval) than toward the lane center (18.75% for the [<−10°,0°[interval).

Regarding data on the vertical axis, the ANOVA revealed that the mean deviation of gaze to the tangent point significantly increased as a function of the visual gain ($F(2,22) = 4.54$, $p < .05$, $\eta^2 = .30$; Table 2). The 3 visual gains × 22 angular deviations ANOVA yielded a significant main effect of angular deviation ($F(21,231) = 74.47$, $p < .0001$, $\eta^2 = .87$), and a significant interaction between the visual gain and the angular deviation ($F(42,462) = 2.57$, $p < .0001$, $\eta^2 = .19$; Fig. 3). When comparing the percentage of gaze points on each side of the tangent point, many more fixations were made further ahead of the tangent point (83% for the [0°,>10°] interval) than the area ahead from the vehicle (17% for the [<-10°, 0°[interval). The peak of gaze point distribution was in the [1°, 2°[interval for all conditions, but the post hoc test revealed that the proportion of gaze in this interval was significantly higher in the no-roll condition than in the roll conditions ($p < .001$). Overall, the higher the visual roll, the more the distribution was skewed beyond the tangent point. This resulted in significant differences in the [0°, 1°[interval, with a lower proportion of gaze for gain 0.4 than for gains 0 and 0.2. Conversely, more gaze points were observed in the [3°,4°[and [4°,5°[intervals for gain 0.4 than for gain 0 (all *ps* < .05). Gain 0.2 gave rise to intermediate results, with non-significant differences with the two other conditions.

3.4. Riding behavior

Data that describe vehicular control are given in Table 3. The analyses revealed a non-significant effect of the visual gain on the mean speed, but a significant main effect of the experimental condition on the mean distance to the lane center ($F(2,22) = 20.25$, $p < .001$, $\eta^2 = .65$), the standard deviation of the lateral position ($F(2,22) = 6.64$, $p < .01$, $\eta^2 = .38$) and the number of lane departures ($F(2,22) = 11.16$, $p < .001$, $\eta^2 = .50$). Post-hoc tests showed that the deviation from the lane center significantly increased between the no-roll and roll conditions, that the variability of vehicle trajectory increased in the 0.4 gain condition in comparison with the two other conditions, and that the number of lane departures increased in the presence of visual roll motion.[1]

3.5. SSQ

With regard to the results for the SSQ, scores were extremely low when compared with the highest possible global score (300). Our results for the SSQ are detailed in Table 4. A first ANOVA was run on the global scores (for pre- and post-sessions), with the visual gain as the independent variable, to determine whether the experimental condition had an effect independently of the time of completion or the subscale. This analysis did not reveal any effect of the visual gain. Global scores were 4.9, 5.6 and 1.2 for gains 0, 0.2 and 0.4, respectively.

A second repeated measures ANOVA with the visual gain and the time of completion (before versus after each session on the motorbike simulator) as independent variables was run on the global score to determine the effect of simulator exposure as a function of the visual gain. This analysis only revealed that symptoms of sickness increased between the pre- ($M = 5.92$) and post-sessions ($M = 9.87$), $F(1,11) = 13.02$, $p < .01$, $\eta^2 = .54$. The interaction with the visual gain was not significant ($F(2,22) = 1.41$, $p = .26$).

Similar analyses that were run for the three subscales only revealed a main effect of the time of completion on the ocular disturbance subscale ($F(1,11) = 9.51$, $p < .05$, $\eta^2 = .46$), and an increasing level of sickness between the two times of completion ($M = 7.1$ and 10.5 before and after riding the simulator, respectively). The effect of this factor on the two other subscales approached significance (*ps* = .06). A final analysis was carried out to compare scores for the subscales in order to determine whether participants had more or fewer symptoms with each subscale. No effect was revealed.

[1] To get a more qualitative view of lane departures, we extracted the mean distance of the motorcycle to the inner edge line during each lane departure. The goal was to explore whether or not riders lost control in the corresponding bends in which cases the motorcycle would move increasingly away from the edge line. This loss of control could potentially be due to over-speeding, for instance. Data showed that the distance to the edge line was 17 cm for the only lane departure in the Gain 0 condition, and 32 and 21 cm in average in the Gain 0.2 and 0.4 conditions, respectively. These relatively short distances to the inner edge line of the road suggest that drivers did not lose control but rather that they occasionally made slight (over) steering errors under the influence of visual roll motion.

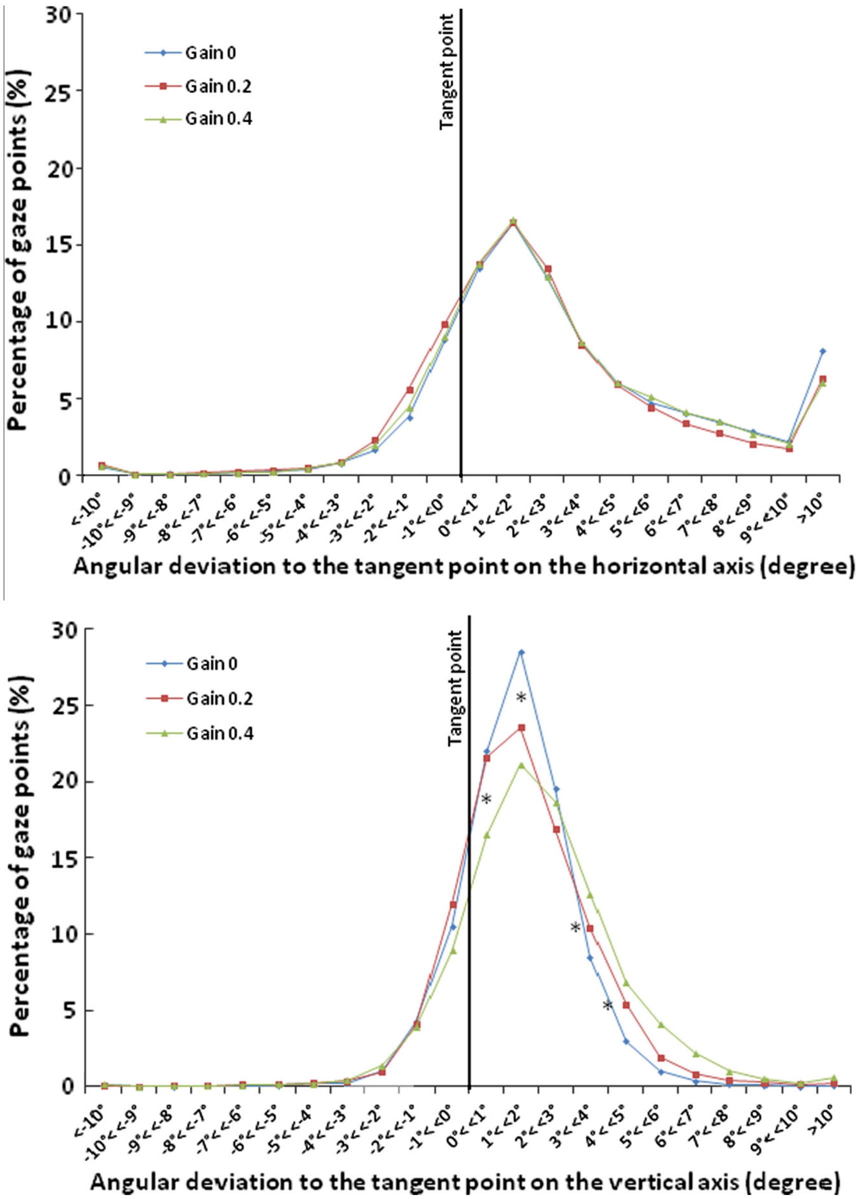

Fig. 3. Percentage of gaze points as a function of the angular deviation (in °) to the tangent point on the horizontal (upper panel) and vertical direction (lower panel).

Table 3
Mean and standard deviation for speed, lateral position, variability of the lateral position and number of lane departures as a function of visual gain.

	Gain 0	Gain 0.2	Gain 0.4
Speed (km/h)	105 (3.9)	104 (4.6)	107 (4.3)
Distance to the lane center (cm)	48.3 (32.2)	60.5 (31.5)	65.6 (31.2)
Variability of the lateral position (cm)	29.3 (10.3)	30.6 (11)	32.9 (12)
Number of lane departures	1	12	13

4. Discussion

The goal of the present study was to examine the effects of visual roll tilt on gaze and riding behavior when negotiating bends on a motorcycle simulator. In the discussion, we will first focus on gaze and riding measures in the control condition

Table 4
Global score for the SSQ and scores for the subscales as a function of visual gain and time of completion.

	Gain 0		Gain 0.2		Gain 0.4	
	Before	After	Before	After	Before	After
Nausea	3.18	5.56	1.59	4.77	3.18	3.18
Oculomotor disturbance	7.58	11.37	6.31	11.37	7.58	8.84
Disorientation	4.64	12.76	4.64	11.6	5.8	8.12
Global	6.23	11.22	4.98	10.59	6.54	7.79

(gain 0) to gain an insight into the visual control of steering in motorcycle riding. We will then discuss the effects of visual roll tilt on the relationship between gaze orientation relative to the tangent point and steering behavior.

4.1. Visual control of steering in a motorcycle simulator

According to the two-level model of steering control in car driving (Donges, 1978), drivers rely on near and far road information, which respectively feeds synergistic, compensatory and anticipatory mechanisms. Recently, several proposals were put forward to enrich this model in terms of visual behavior. Lehtonen et al. (2014) proposed a hierarchical three-level model of steering through bends and characterized each level with associated types of fixations and targeted information. The stabilizing level uses steering points in the near zone and helps to regulate the vehicle position in the lane. The guidance level relies on steering points in the far region and ensures steering smoothness. The steering point could be either the tangent point (Kandil et al., 2009; Land & Lee, 1994; Wilson et al., 2007), points on the road that drivers want to pass (Wann & Swapp, 2000; Wilkie & Wann, 2003), or the boundaries of a safe trajectory envelop that drivers do not want to cross (Mars & Navarro, 2012). Beyond the guidance level, trajectory planning focuses on speed and path planning and is supported by anticipatory eye movements into the distance, towards the direction of the bend. These look-ahead fixations, which are characterized by a high eccentricity, are dedicated to the acquisition of information of a more tactical nature than guiding fixations (Mars & Navarro, 2012). In the context of cycling, Vansteenkiste, Cardon, D'Hondt, Philippaerts and Lenoir (2013) sought to explain human visual behavior in goal-directed locomotion in terms of a tight coupling between near and far information (in a similar way to the two-stage model) that is influenced by task and environmental constraints. Gaze toward the near region would increase with task complexity but decrease with experience and driving skills. Gaze to the far region would be needed if speed and/or environmental uncertainty increased. In fact, gaze was more directed to the near region when the path width or the quality of the road decreased (Vansteenkiste, Cardon, D'Hondt, Philippaerts, & Lenoir, 2013; Vansteenkiste, Zeuwts, Cardon, Philippaerts, & Lenoir, 2014). Compared with car drivers, the gaze fixations of motorcyclists were more frequently located on the road surface, in order to detect any irregularities or hazards (Nagayama et al., 1980). Gaze was also less distant for less experienced drivers (Mourant & Rockwell, 1972) and the number of look-ahead fixations in bends decreased when mental workload increased (Lehtonen, Lappi, & Summala, 2012). Conversely, higher speeds resulted in more distant gaze behavior (Vansteenkiste, Cardon, D'Hondt, Philippaerts, & Lenoir, 2013).

These theoretical considerations might help us to understand gaze and steering results obtained when riding a motorbike simulator. In the control condition, our results revealed that the peak of gaze point distribution was deviated beyond the tangent point by a visual angle of 2° on the horizontal and vertical axes. This sort of behavior suggests that motorcyclists did not track the tangent point proper, but rather a steering point on the road ahead. It is compatible with the "look where you want to steer" hypothesis (Mars & Navarro, 2012; Wilkie & Wann, 2003) and is in line with the recommendations of advanced riding manuals (e.g., Ienatsch, 2003; Motorcycle Safety Foundation, 2004). These stress the importance of adopting relevant visual strategies to improve safety; in particular, they advocate that riders move their eyes from key point to key point on the road as they progress (Wilkie, Wann, & Allison, 2008). Our results also highlighted a massive deviation of gaze towards the direction of the bend exit, with more than 80% of gaze points directed beyond the tangent point in the horizontal direction. This figure is higher than would be the case in car driving simulator studies (for similar analyses performed on car drivers, see Mars & Navarro, 2012). This deviation suggests that motorcyclists looked for a steering point that was well beyond the tangent point for most of the time. They may also have made a greater number of look-ahead fixations to support trajectory planning (Lehtonen et al., 2014). This increase in anticipation by our participants may be explained by a combination of high speed, unobstructed pathways and open view conditions. Whatever the case may be, it does not fit well with the tangent point hypothesis in the strict sense, as was originally put forward by Land and Lee (1994).

4.2. Effects of visual roll on gaze direction and steering control

Previous research that supported the idea of using visual roll in motorbike simulation mainly relied on subjective reports (Cossalter et al., 2010; Kageyama & Tagami, 2002; Shahar et al., 2014; Stedmon et al., 2011). Likewise, in the present experiment, roll conditions were seen as being preferable to the no-roll condition. Nine out of twelve participants ranked the 0.2 and 0.4 gain conditions as being first, and six out of these nine participants ranked the 0.4 gain condition as being first. In addition, roll conditions did not lead to sickness symptoms, contrary to previous research in which the amount of visual roll motion was twice as large as that in the present study (Lobjois et al., accepted for publication). However, previous studies have shown significant differences between the subjective and objective effects of the various features that make up a virtual environment (e.g., Morice, Siegler, & Bardy, 2008). The present study aimed to go beyond subjective assessments, through an analysis of the consequences of visual roll tilt on gaze behavior and steering control.

With regard to riding performance, our results revealed that the mean lateral position was deviated further away from the center of the lane, toward the inside road edge line, when the visual scene was rolled. This trend to further cut the corner as a function of visual gain may appear to reflect a strategy to optimize progression in the bend (Crundall et al., 2012). However, it was accompanied by a markedly increased number of lane departures. Furthermore, according to the results, the steering stability decreased as a function of roll gain, as attested by the increased variability of the vehicle's lateral position. Taken together, this pattern of results suggests that the control of steering was degraded by the introduction of visual roll in the simulation. Furthermore, the visual roll seems to have an all-or-nothing impact, as the degradation of steering control was not proportional to the roll gain.

At the same time, results confirmed that the dynamics of the visual scene were modified with the introduction of roll tilt. The roll angle magnitude increased as a function of the visual gain, and the motion range of the tangent point increased in the vertical direction only. Based on the tight coupling between gaze behavior and steering control, the reduction in the quality of steering control may then be explained by a roll-induced modification of gaze behavior. Whereas the horizontal distribution of gaze points relative to the tangent point was preserved as expected, the vertical distribution was modified by the roll conditions. The higher the roll gain, the wider the distribution of gaze points, with more guiding fixations further down the road at various eccentricities. With roll, riders may have had difficulty in stabilizing the guiding fixations at a distance that contains the critical information for tracking changes in road curvature; consequently, gaze control was less sharp and, on average, preview distance was greater. This increase in preview distance may also be interpreted as the result of more weight being given to advanced trajectory planning. According to Lehtonen et al. (2014), anticipation can be considered at two different levels: guidance and planning. Trajectory planning receives information from look-ahead fixations, which are characterized by a high eccentricity, but may also be found at closer distances on the road. Our results did not show any increase in look-ahead fixations. However, the shift of the gaze distribution towards parts of the road located higher in the visual field may represent an attempt to reinforce planning when guidance becomes more difficult.

Roll tilt may also have introduced important variations in peripheral vision, as roll was also added to the edge lines in the near zone. This may have disrupted the stability of steering, as attested by the increased variability of the lateral positioning in the high gain condition. The trend to further cut the corner as a function of visual gain may then be seen as a way of compensating for the increased distance to the inside edge line rather than as a pure strategy to optimize progression in the bend (Crundall et al., 2012).

Finally, in this study, the leaning sensation was only induced by the manipulation of visual information. However, in the most advanced dynamic motorcycle simulators, the leaning sensation is rendered by coupling visually-specified and inertially-specified roll motion. When roll motion of the simulator mock-up is introduced into the simulation, there are two main motion cueing algorithms that are used to transform motion of a real motorcycle into motion for the simulator. With the classical washout algorithm (e.g., Cossalter et al., 2010), sustained acceleration when entering a curve is filtered and transformed into an onset cue. Then, the simulator moves back to its initial position under the motion perception threshold and the leaning illusion is only provided by the tilted visual scene. With this technique, most of the roll angle is delivered through the visual dimension. When the intended leaning illusion, i.e. the maximum roll angle, is large, this is likely to induce the changes we observed in the gaze distribution and steering control. Another motion cueing algorithm is based on the restitution of both visually and inertially-specified roll motion throughout the bend (e.g., Benedetto et al., 2014; Kageyama & Tagami, 2002). In this case, the tilting of the visual scene and the rolling of the motion platform work together to reproduce the overall roll angle. Although the physical tilting is necessarily limited in order to avoid falling from the motorcycle, it allows reducing the amount of visual roll. The question arises whether this reduction may limit the effects of visual roll tilt on gaze behavior and steering control. On the other hand, it would be interesting to explore whether the changes we observed in the gaze distribution and steering control would be increased with visual roll motion of larger magnitude.

5. Conclusion

This study investigated the visual control of steering in a riding simulator. Using the tangent point as a dynamic spatial reference to analyze gaze distribution, our results have highlighted the fact that motorcyclists track control points on the road further ahead from the tangent point; this is compatible with the "steer where you look" hypothesis (Mars & Navarro, 2012; Wilkie & Wann, 2003). However, this visual behavior was influenced by the introduction of visual roll. Gaze directions were less sharp, with more fixations directed further ahead down the road. Although the visually induced experience of leaning was clearly accepted by the riders, this shift in visual behavior was coupled with a degradation of steering stability and an offset in lateral positioning, which sometimes led to lane departure. It is in accordance with previous research showing that degradation in the near and far visual signal led to a deviation in the trajectory and an increase in the variability of the lateral position (Frissen & Mars, 2014). This argues in favor of a limited use of roll tilt to mirror the riding experience of leaning in using a motorbike simulator for bend negotiation. Finally, this study demonstrates the necessity to tackle the underlying processes of driving performance to get a clear view of the effects of simulator configuration on the operators' behavioral responses and adaptation.

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