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Influence of risk expectation on haptically cued corrective manoeuvres during near lane departure

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Some driving devices are designed to prevent road departures. One such device, motor priming (MP), provides small pulses to the steering wheel towards the lane centre, without correcting the trajectory itself. Compared with the other lane departure warning systems, its higher efficacy has been demonstrated; it is hypothesised that this relies on the action of haptic cues at the sensorimotor level (Navarro, J., Mars, F., and Hoc, J.M., 2007. Lateral control assistance for car drivers: a comparison of motor priming and warning systems. *Human Factors*, 49 (5), 950–960). The way in which corrective manoeuvres, primed by MP, can be influenced by processes that operate at higher levels of cognitive control, such as risk evaluation, is an issue. Results showed that MP improved all indicators of steering efficiency, starting with reaction times. Risk expectation and situation analysis did not influence reaction times but came into play soon after the corrective manoeuvre was initiated. Thus, although MP triggered the response at the sensorimotor level, higher levels of cognition (symbolic control) quickly modulated the execution of the corrective manoeuvre.

Practitioner Summary: This paper showed that corrective manoeuvres following directional pulses on the steering wheel (motor priming) are modulated by risk expectation. The conclusion may be of interest for designers of haptics-based automation such as lane departure warning and lane keeping assistance systems.

Keywords: human–machine cooperation; driving assistance device; cognitive control; steering behaviour

Introduction

Lane departure is a major feature of car accidents. In the United States, for example, it is a factor in 66% of accidents involving just one light vehicle (Najm *et al*. 2007). As the search for solutions to this problem progresses, driving assistance devices are becoming increasingly sophisticated. One complication is that drivers need to be supported in many contexts (Baldwin 2011). In fact, each class of situation needs a specific intervention with a certain degree of automation (Parasuraman *et al*. 2000). For example, smooth deviation in straight lines does not need the same intervention as distraction close to a bend. One should also take into account the voluntary risk-taking behaviours of some drivers (Jonah 1997). Consequently, several types of devices have been designed (Hoc *et al*. 2009, Navarro *et al*. 2011). For example, lane departure warning systems (LDWS) are created to improve a driver's alertness when a situation becomes dangerous. Such a device applies mutual control (or cross-checking) of the driver's task (Hoc *et al*. 2009). It intervenes to criticise the driver's action. By way of contrast, lane-keeping assistance systems (LKAS) share control of the vehicle with the driver (Griffiths and Gillespie 2005). As long as drivers are legally responsible for their vehicle, they will need to be able to control and adapt their action to various contexts with many unpredictable events. Thus, in whatever way an assistance device intervenes, the driver should stay in charge of steering the vehicle and be able to modulate or inhibit the manoeuvres suggested by the device (Abbink *et al*. in press).

This idea is particularly important with a device called 'motor priming' (MP), which has been proposed by Navarro *et al*. (2007, 2010). In cases of near lane departure, the device provides mild steering pulses towards the lane centre. These pulses do not correct the trajectory itself, but preactivate (prime) the corrective gesture. Results gathered by Navarro *et al*. (2007, 2010) support the idea that MP not only improves situation diagnosis, in the same way as warning systems can facilitate the orientation of visuospatial attention (Ho *et al*. 2006), but also acts at the motor level by providing some directional cues to the hands via the haptic modality. As such, it aims to improve on warning systems with only minimal intervention on the steering wheel, in contrast to corrective LKAS.

In their studies of a device which also uses a directional pulse on the steering wheel, Suzuki and Jansson (2003) found that some drivers turned the steering wheel in the wrong direction. Such erroneous responses may be

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explained, in part at least, by the lack of explanation given to the participants. Alternatively, directional pulses may have induced the drivers to make reflexive counteractions, turning the steering wheel without considering the driving context. Indeed, Kullack *et al.* (2008) proposed a system called ReflekAS, based on the principle that steering pulses in the direction of lane departure can elicit fast and stereotyped responses in the opposite direction. Thus, when designing assistance devices that act at the level of motor control, one must take the utmost care to examine the ability of drivers to stay in full control of their vehicle.

The present paper specifically addresses the question of how responses elicited by MP may be modulated by taking the context into account. Indeed, modulation, like inhibition, is a critical test used to discriminate between voluntary and reflexive movements (Prochazka *et al.* 2000). When MP intervenes during lane departures, drivers interpret the situation and need to stay in control of their vehicles. In other words, even though MP prompts drivers to take action in a given direction, they need to be able to modulate their steering responses in relation to the current situation.

Situations that are identical from the point of view of the automated device can correspond to various levels of perceived risk from the driver's point of view. One example is the well-documented practice of cutting bends (Mars 2008, Couton-Jean *et al.* 2009). From a purely geometric analysis, the vehicle is close to crossing one of the edge lines; from the driver's point of view, however, cutting a bend reduces lateral acceleration and thus offers a more comfortable way of driving.

In actual fact, humans analyse contextual elements and corresponding risk according to different levels of cognition, operating from highly symbolic representations or subsymbolic perceptual cues. In order to illustrate this point, Lewis-Evans and Charlton (2006) identified the effects of behavioural adaptation on drivers' speed and lateral displacement in response to manipulations of road width. Their results underline the inability of participants to identify changes in road width, which suggests that risk was processed below the level of consciousness. On the other hand, at the symbolic level, humans integrate potential danger in their situation analysis. For example, the consequences of lane departure are not the same when driving on roads surrounded by flat, open fields as they are on roads on the edge of a ravine. One conclusion could be that, as a last resort, analysis of the context should allow drivers to modulate the effects of assistance devices in relation to the level of perceived hazard.

According to Michon (1979), a *hazard* is a situation within which there is some probability that danger could occur; in other words, it is the danger causal field that influences the gravity of that situation and the probability of danger (Hoc 1996). So, from the driver's point of view, a *risk* can be understood as the danger and the probability of its occurrence. Thus, the aim of driving assistance devices, including MP, is to reduce the gravity of the hazard and, consequently, the risk of road departure. It remains to be determined how drivers cope with the different levels of danger; something which is not taken into account by the devices themselves. This is especially the case in the context of dynamic situations with high temporal pressure, such as when lane departure is imminent.

It is acknowledged that driving is a dynamic situation in which different levels of control interact (Michon 1985). The model of cognitive control proposed by Hoc and Amalberti (2007), which emphasises the roles and interrelations of four main control modes, is a good choice for interpreting levels of intervention of MP and context analysis. In this model, two dimensions are crossed - symbolic vs. subsymbolic control, and external vs. internal control. The level of abstraction of the data required for control (symbolic vs. subsymbolic) is very close to the Skill-Rule-Knowledge model introduced by Rasmussen (1986) and can be understood as a continuum between two opposite levels of control. Symbolic control is close to the processes that are conscious or controlled, whilst subsymbolic control can be understood as something more automated, close to the sensorimotor control loops. Hoc and Amalberti (2007) highlighted the role of (symbolic) supervision, which calibrates the execution of (subsymbolic) routines, as previously modelled by Anderson *et al.* (2004).

Within the framework of Hoc and Amalberti's model, MP can be understood as a first intervention at a subsymbolic (motor) level, which is then validated by symbolic control (situation diagnosis). Hence, even though MP acts at the subsymbolic level, the driver should be able to choose whether or not to perform the primed response, calibrate it or even stop its execution by means of supervision. This assertion will be studied using two strengths of MP; the first is similar to the MP used by Navarro *et al.* (2007, 2010); the second is three times stronger. This factor has been introduced because it is hypothesised that the reflexive counteractions reported by Suzuki and Jansson (2003) and Kullack *et al.* (2008) result from stronger torque pulses; these may tap into lower sensorimotor neural systems that are lower along the continuum between symbolic and subsymbolic processes. Two other hypotheses are made. First, the subsymbolic intervention of MP will reduce the risk of lane departure by improving drivers' responses. Second, risk expectation resulting from the symbolic processing of the context will lead to the modulation of the MP's influence on response execution.

Method

Participants

Eighteen subjects (14 males, 4 females, 27 years of age on average) participated in the study. Gender was not balanced since previous studies on the effect of haptic collision avoidance system showed no effect of gender on the perception of haptic intensity, reaction times or the control of lateral position (Stanley 2006).

All drivers had held a driving licence for at least two years (mean = 8.6 years). Self-reported annual mileage for the past year ranged from 1,000 to 35,000 km (mean = 11,000 km). None of them was familiar with LDWS. No motion sickness was observed. At most, a very mild sensation of heat (without nausea) was reported by a few participants.

Equipment

The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with full instrumentation. It was equipped with an active steering system for realistic 'scale one' force-feedback. The SCANNeRII® (http://www.scanersimulation.com/) software package was used with the CALLAS® dynamic vehicle model (Lechner *et al.* 1997). The visual environment was displayed on three 32-inch LCD monitors, one in front of the driver and two laterals, inclined at 45° from the front one. The monitors were viewed from a distance of about 1 m and covered 115° of visual angle in width and 25° in height. The graphics database reproduced a country environment.

Driving assistance device

Three driving conditions were tested, one without assistance and two with different MP strengths (light and strong MP). MP delivers small asymmetric oscillations on the steering wheel when the car is about to cross one of the lane edge lines (Figure 1). The first movement of the steering wheel and every second movement are directed toward the road centre, with a stronger and shorter torque pulse (2 N/m for light MP and 6 N/m for strong MP, lasting 100 ms) than those directed towards the side of lane departure (0.5 N/m for both light and strong MP, lasting 200 ms). MP was delivered during a one-second period with an oscillation frequency of 3.3 Hz.

Procedure

The experiment lasted for 60 min. First, participants were asked to adjust the seat position so as to achieve a realistic and pleasant driving posture. They were asked to hold the steering wheel with both hands, in the '10-to–2' position. This hand positioning was to be maintained throughout the experiment. They then drove for 10 min in order to become accustomed to the simulator. Participants were instructed to drive in the right lane, as they usually would, and to respect a speed limit of 70 km/h. The functioning principle of the assistance device was explained.

The experiment consisted, for all drivers, in performing four complete laps of a country road route for each driving condition. Each lap lasted three minutes and corresponded to a distance of about 3 km. The road was a single-carriageway road with two lanes mixing curved and straight sections. It consisted of eight straight lines and 11 bends, seven turning to the left and four turning to the right. The driving lane was 3 m wide and delineated with a broken centreline and a continuous edge line. Some intersections were present and other occasional vehicles were simulated encouraging participants to remain in their own lane.

In order to assess the effects of driving assistance and risk expectation independently of any contextual factors, it was essential to provoke very similar lane departure incidents in all situations. To this end, visual occlusions were

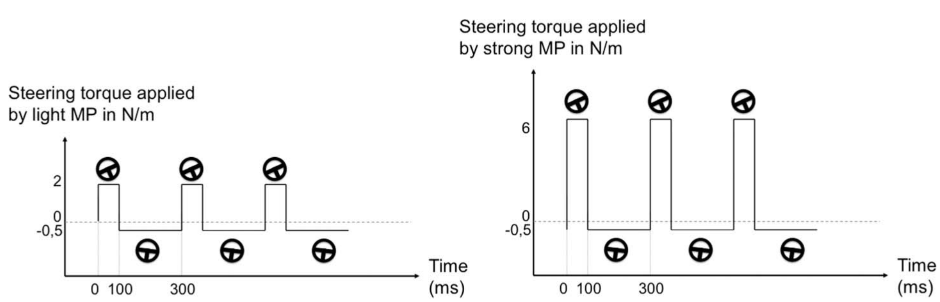

Figure 1. Schematic representation of light and strong MP in action during a lane departure to the right. Left: light MP; Right: strong MP.

chosen (Brookhuis *et al*. 2003). This was achieved by suddenly blackening all screens. This technique is more traditionally used to evaluate how much visual input the driver needs to maintain good lane-keeping performance when using in-vehicle systems (Godthelp *et al*. 1984, van der Horst 2004). In the present experiment, visual occlusions permitted high control of the timing and positioning of lane departure events. They could occur at four different positions, but only two occurred per lap. They were, thus, relatively unpredictable. Experimental scenarios were structured in such a way that no oncoming vehicle was present just before and after a visual occlusion. Two occlusions were positioned in bends of similar large curvature (300 m on the left bend and 225 m on the right bend), one leading to lane departure to the right, the other to the left. The others took place in straight lines, also in two directions. When visual occlusion occurred, participants were asked to stop making adjustments to steering. Thus, visual occlusions that occurred when entering bends caused a natural lane departure toward the outside edge line in left bends and toward the centreline in right bends. In order to standardise the direction of lane departure in straight lines, a slight and imperceptible shift in the vehicle heading was introduced when the visual occlusion occurred. Drivers recovered vision when lane departure was imminent: this is precisely the point at which the driving assistance device was put into action.

Following simulator training, two levels of risk expectation were introduced to driving assistance conditions. During visual occlusion, either 'Minor risk' (in green) or 'Warning! Major risk' (in red) was displayed on the screen (Figure 2). In addition, in the major risk situation, traffic cones appeared on the edge of the road to confirm the cost of the lane departure. Thus, the level of risk was manipulated at the symbolic level, independently of perceptual cues that would have informed on imminent lane departure if drivers had been allowed to see they were drifting out of lane. Although these two levels of risk processing can hardly be dissociated in real conditions, the use of textual warning allowed the subjective evaluation of risk to be specifically manipulated. Assistance setting (without assistance, light MP, strong MP) and risk expectation (minor risk, major risk) were fully counterbalanced.

Data analysis

Figure 3 represents the relation between all dependent variables that were analysed to assess performance. The main variable was the time spent by drivers outside the safety envelope of ± 80 cm from the lane centre after the end of the visual occlusion (duration of lateral excursion: DLE). The steering reaction time (SRT) corresponded to the time

Figure 2. Two levels of induced risk. Left: minor risk; Middle: major risk; Right: traffic cones following major risk induction.

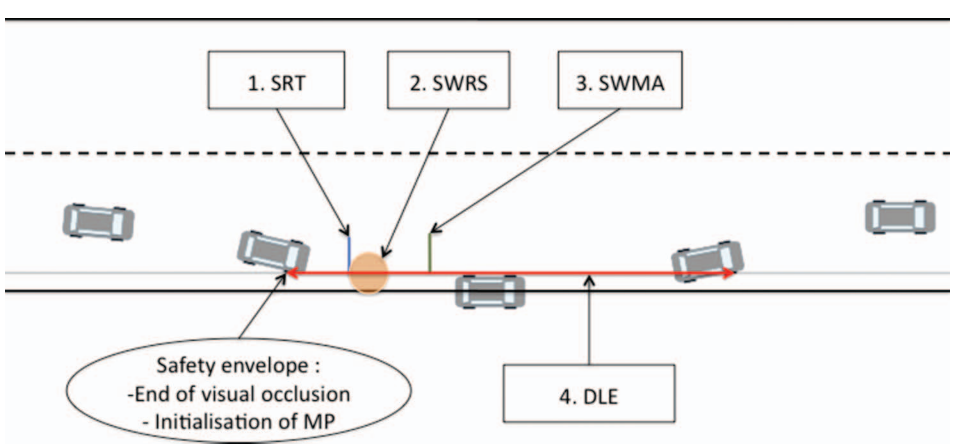

Figure 3. The four variables; 1. Steering Reaction Time (SRT); 2. Peak of Steering Wheel Rotation Speed (SWRS); 3. Steering Wheel Maximum Angle (SWMA); 4. Duration of Lateral Excursion (DLE).

elapsed between the end of the visual occlusion and the time when drivers began to act on the steering wheel. The peak of steering wheel rotation speed (SWRS) was used to evaluate the sharpness of the steering movement when it was initiated. It was computed during the 450 ms following the start of the steering response. Finally, the steering wheel maximum angle (SWMA) corresponded to the magnitude of the steering reaction.

The significance of the effects of all independent variables was assessed for DLE, SRT, SWRS and SWMA by repeated measures ANOVAs. In addition, the population effects sizes were evaluated on the basis of fiducial inference. Fiducial inference (Rouanet and Lecoutre 1983, Rouanet 1996, Lecoutre and Poitevineau 2005) is a variant of Bayesian statistical inference, aimed at concluding on the population effect size (δ) on the basis of the observed effect (d), the sample size and variability. It goes beyond the test of significance, which only concludes in terms of the existence of a non-null effect. In this paper, we will only give the conclusions on effect sizes with a guarantee of 0.90. For example, '$\delta > 20$' will mean 'the probability for δ being greater than 20 is 0.90'. Paired comparisons tested the effects of the two levels of MP strength relative to the condition without assistance. When both tests concluded a significant and notable effect of MP, a third comparison between light and strong MP was performed.

Results

Right and left lane departures gave rise to very similar patterns of results. Thus, analyses were regrouped, both in bends and in straight lines. Furthermore, at no point did corrective manoeuvres lead the car into the opposite lane. Hence, whatever the speed and magnitude of steering wheel corrections, the vehicle was brought back close to the lane centre with no significant overshoot toward the opposite lane.

Lateral excursions were shorter in straight lines because it is easier and quicker to return to a safe position in these cases (Table 1 and Figure 4). So, no comparison between bends and straight lines was performed.

Duration of lateral excursion

The DLE without assistance and with a minor risk was, on average, 2.16 s in bends and 1.83 s in straight lines. The device (A) and risk expectation (R) had significant effects in bends or in straight lines, without significant interaction (Table 1 and Figure 4).

In bends, the effect of strong MP was greater ($\delta > 0.43$ s) than the effect of light MP ($|\delta| < 0.23$ s). Risk expectation also reduced the DLE by about 0.14 s. In the major risk condition, drivers were quicker to return toward a safe position than in the minor risk condition ($\delta > 0.08$ s).

In straight lines, the effect of strong MP ($\delta > 0.33$ s) was greater than the effect of light MP ($|\delta| < 0.23$ s). In the major risk condition, drivers were quicker to return toward a safe position than in the minor risk condition ($\delta > 0.05$ s).

Thus, light and strong MP reduced the DLE in bends and in straight lines. Strong MP was more efficient than light MP. Moreover, the manipulation of risk expectation by means of instructions had a systematic effect on DLE in bends and in straight lines.

Steering reaction time

The SRT without assistance and with a minor risk was, on average, 492 ms in bends and 473 ms in straight lines. The device, but not risk expectation, had a significant effect in bends or in straight lines, without significant interaction (Table 1 and Figure 5).

In bends, the effect of light MP ($\delta > 36$ ms) and strong MP ($\delta > 65$ ms) were notable and significant when compared to the control condition, with a significant difference between them ($\delta > 20$ ms). The effect of risk was negligible ($|\delta| < 13$ ms).

In straight lines, the device notably reduced the SRT (Light MP: $\delta > 28$ ms; strong MP: $\delta > 20$ ms), with no significant difference between them ($|\delta| < 02$ ms). As for bends, the effect of risk was negligible ($|\delta| < 14$ ms).

In sum, MP reduced SRT in bends and in straight lines, with no effect of risk expectation.

Peak of steering wheel rotation speed

The SWRS without assistance and with a minor risk was, on average, 183°/s in bends and 138°/s in straight lines. The device and risk expectation had significant effects in bends or in straight lines, without significant interaction (Table 1 and Figure 6).

Table 1. Analyses performed on bends and straight lines.

Variable	Geometry	Comparison	*D*	Bayesian conclusion	Test	LoS
DLE: Duration of lateral excursion (s)	**Bends**	A.R	0.11	$\|\delta\| < 0.23$	$F(2,24) = 0.75$	$P > .48$
		A	0.57	$\delta > 0.43$	$F(2,24) = 29.04$	$P < .0001$
		a1,a2	0.14	$\delta > 0.08$	$t(12) = 1.48$	$P > .16$
		a1,a3			$t(12) = 5.73$	$P < .0001$
		R			$t(12) = 3.31$	$P < .007$
	Straight lines	A.R	0.13	$\|\delta\| < 0.23$	$F(2,24) = 0.07$	$P > .92$
		A	0.46	$\delta > 0.33$	$F(2,24) = 20.50$	$P < .0001$
		a1,a2	0.13	$\delta > 0.05$	$t(12) = 1.98$	$P < .08$
		a1,a3			$t(12) = 5.07$	$P < .0001$
		R			$t(12) = 2.43$	$P < .04$
SRT: Steering reaction time (ms)	**Bends**	A.R	54	$\delta > 36$	$F(2,24) = 1.43$	$P > .25$
		A	83	$\delta > 65$	$F(2,24) = 29.41$	$P < .0001$
		a1,a2	29	$\delta > 20$	$t(12) = 4.18$	$P < .002$
		a1,a3	06	$\|\delta\| < 13$	$t(12) = 6.67$	$P < .0001$
		a2,a3			$t(12) = 4.52$	$P < .0001$
		R			$t(12) = 1.06$	$P > .30$
	Straight lines	A.R	42	$\delta > 28$	$F(2,24) = 0.12$	$P > .88$
		A	40	$\delta > 20$	$F(2,24) = 8.68$	$P < .002$
		a1,a2	02	$\|\delta\| < 02$	$t(12) = 4.21$	$P < .002$
		a1,a3	07	$\|\delta\| < 14$	$t(12) = 2.74$	$P < .02$
		a2,a3			$t(12) = 0.24$	$P > .41$
		R			$t(12) = 1.58$	$P > .13$
SWRS: Steering wheel rotation speed (°/s)	**Bends**	A.R	57	$\|\delta\| < 77$	$F(2,24) = 1.55$	$P > .23$
		A	134	$\delta > 114$	$F(2,24) = 40.20$	$P < .0001$
		a1,a2	38	$\delta > 20$	$t(12) = 4.17$	$P < .002$
		a1,a3			$t(12) = 9.59$	$P < .0001$
		R			$t(12) = 3$	$P < .02$
	Straight lines	A.R	82	$\|\delta\| < 99$	$F(2,24) = 1.47$	$P > .24$
		A	160	$\delta > 138$	$F(2,24) = 61.19$	$P < .0001$
		a1,a2	24	$\delta > 13$	$t(12) = 6.33$	$P < .0001$
		a1,a3			$t(12) = 10.29$	$P < .0001$
		R			$t(12) = 3.18$	$P < .009$
MASW: Maximum angle of steering wheel (°)	**Bends**	A.R	10	$\delta > 6$	$F(2,24) = 0.21$	$P > .81$
		A	24	$\delta > 19$	$F(2,24) = 36.70$	$P < .0001$
		a1,a2	13	$\delta > 10$	$t(12) = 3.89$	$P < .003$
		a1,a3	14	$\delta > 6$	$t(12) = 7.69$	$P < .0001$
		a2,a3			$t(12) = 6.68$	$P < .0001$
		R			$t(12) = 3.77$	$P < .003$
	Straight lines	A.R	9	$\delta > 6$	$F(2,24) = 0.54$	$P > .58$
		A	20	$\delta > 17$	$F(2,24) = 70.60$	$P < .0001$
		a1,a2	11	$\delta > 9$	$t(12) = 5.70$	$P < .0001$
		a1,a3	2	$\|\delta\| < 4$	$t(12) = 9.82$	$P < .0001$
		a2,a3			$t(12) = 8.00$	$P < .0001$
		R			$t(12) = 1.45$	$P > .17$

Note: Summary of the statistical analyses performed on the effects of all devices for bends (grey rows) and straight lines (white rows). For each dependent variable and each comparison, the table shows the observed effect (*d*), the Bayesian conclusion on the size of the population effect (δ) with a guarantee of 0.90, the test statistics of the null hypothesis, and the two-tailed level of significance. Formalism used for comparisons: A: Assistance (a1: without assistance; a2: light MP, a3: strong MP); R: Risk expectation; A.R stands for the interaction between A and R; a1,a2 for a1 vs. a2.

In bends, the effect of strong MP was greater ($\delta > 114°/s$) than the effect of light MP ($|\delta| < 77°/s$). Risk expectation also increased the rotation speed of the steering wheel by about 38°/s ($\delta > 20°/s$).

In straight lines, the effect of strong MP was greater ($\delta > 138°/s$) than the effect of light MP ($\delta < 99°/s$). In the major risk condition, drivers rotated their steering wheel more quickly ($\delta > 13°/s$) than in the minor risk condition.

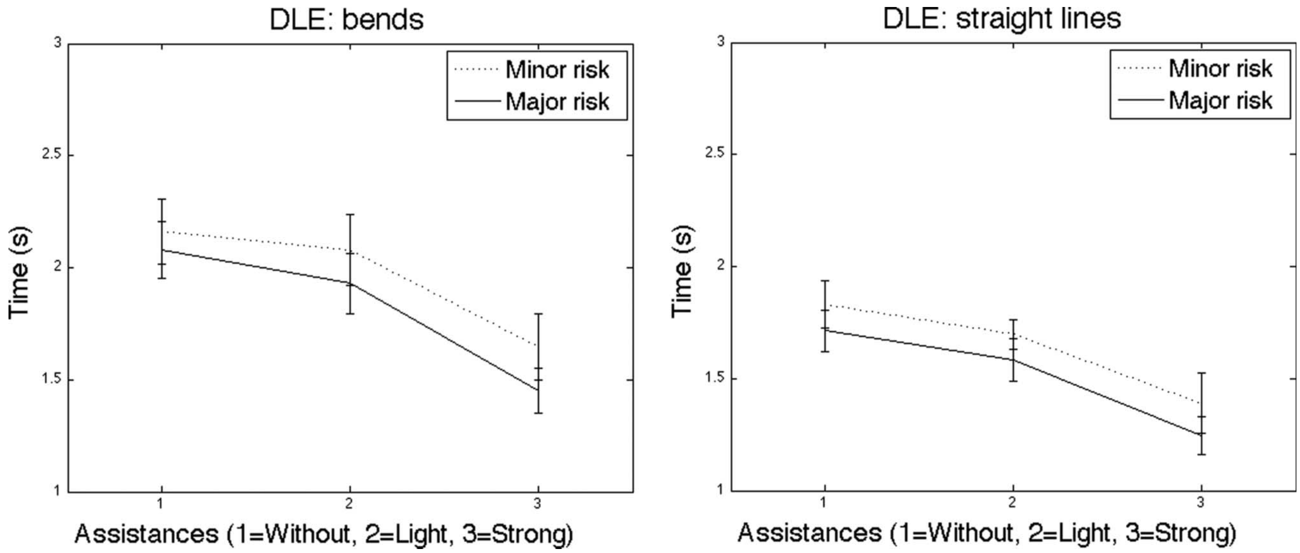

Figure 4. Duration of Lateral Excursion (DLE) in bends (left) and in straight lines (right) as a function of risk expectation. Without: without assistance; Light: light MP; Strong: strong MP. Error bars represent standard errors of means.

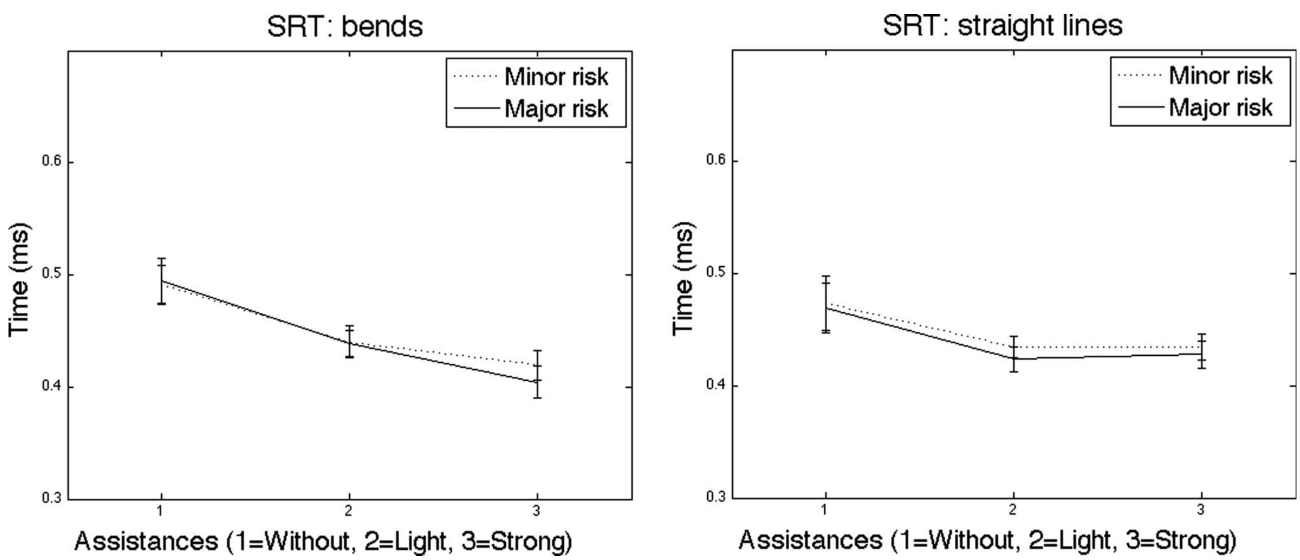

Figure 5. Steering reaction times (SRT) in bends (left) and in straight lines (right) as a function of risk expectation. Without: without assistance; Light: light MP; Strong: strong MP. Error bars represent standard errors of means.

Thus, MP increased SWRS in all cases, with an effect of MP strength; the stronger the MP, the higher the SWRS. Moreover, the manipulation of risk expectation by means of instructions had a systematic effect on SWRS in all cases.

Steering wheel maximum angle

The mean SWMA in conditions without assistance and with a minor risk was, on average, 52° in bends and 32° in straight lines. The device had significant effects in bends or in straight lines, without significant interaction (Table 1 and Figure 7).

In bends, the effect of light MP ($\delta > 6°$) and strong MP ($\delta > 19°$) were notable, with a significant difference between them ($\delta > 10°$). Risk expectation also increased the SWMA by about 14° and had a significant effect. In the major risk condition, drivers adopted a higher angle on the steering wheel than in the minor risk condition ($\delta > 6°$).

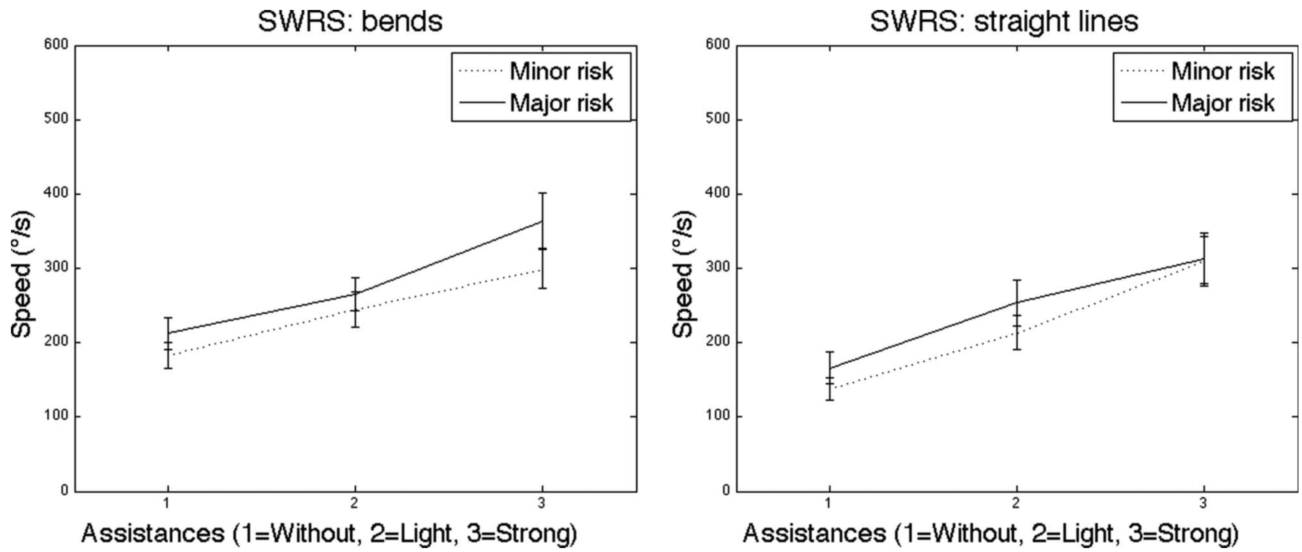

Figure 6. Peak of Steering Wheel Rotation Speed (SWRS) in bends (left) and in straight lines (right) as a function of risk expectation. Without: without assistance; Light: light MP; Strong: strong MP. Error bars represent standard errors of means.

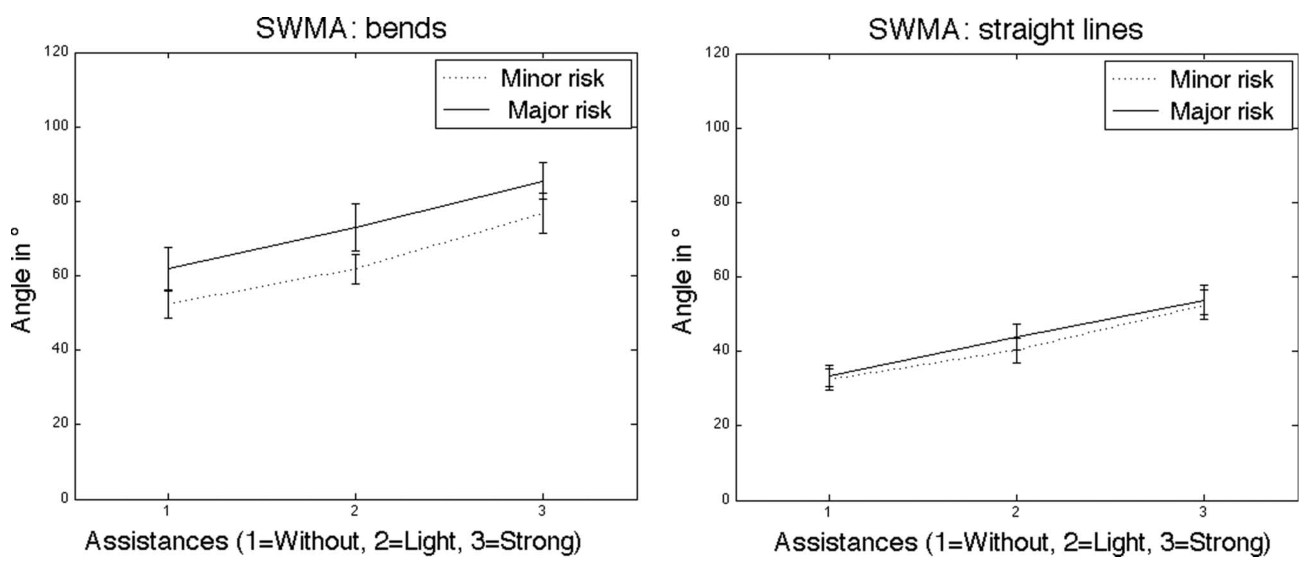

Figure 7. Steering wheel maximum angle (SWMA) in bends (left) and in straight lines (right) as a function of risk expectation. Without: without assistance; Light: light MP; Strong: strong MP. Error bars represent standard errors of means.

In straight lines, the effect of light MP ($\delta > 6°$) and strong MP ($\delta > 17°$) were notable, with a significant difference between them ($\delta > 9°$). The effect of risk was not significant and negligible ($|\delta| < 4°$).

Thus, MP increased SWMA in all cases. The manipulation of risk expectation by means of instructions had a systematic effect on SWMA in bends, but not in straight lines.

Discussion

This experiment investigated the combined influence of risk expectation and MP, an assistance device delivering directional haptic cues on the steering wheel during lane departure episodes. Navarro *et al*. (2007, 2010) examined the same assistance device, comparing the effect it had on recovery manoeuvres with those elicited by various LDWS, including lateralised vibration on the steering wheel (that is directional tactile stimulation of the hands). Navarro's results strongly suggested that MP directly intervenes at the level of sensorimotor control by cueing the motor system; this contrasts with warning systems, which only improve situation diagnosis. The main issue in the present experiment was to determine whether the sensorimotor component of the stimulation left drivers in full (symbolic) control of their reactions. To this end, risk expectation was manipulated. Results show that MP effectively improved lateral control. This was observed on all steering indicators, from response times to the DLE. The stronger MP was, the greater its effects. Risk expectation also had a systematic effect on all indicators, with the exception of reaction times; this emphasises the modulation of the steering response by symbolic processes. The following discussion will examine in detail the respective influence of symbolic and subsymbolic processes in those results.

When MP intervened, drivers were quicker to react. The haptic cue delivered by MP gave directional information to the arm motor system, which reduced response times by a similar amount whatever the level of risk expectation. It suggests that the initiation of the steering response was determined at the subsymbolic level. The influence of risk expectation appeared later during the response execution. Drivers rotated their steering wheel faster, reached a larger maximum steering angle and reduced the DLE when the expected risk was higher. Thus, it appears that drivers took into consideration the hazardousness of the situation to modulate their corrective manoeuvres once it was initiated.

Interestingly, there was one exception to the previous statement. Risk expectation increased the maximum steering wheel angle in bends, but not in straight lines. This could be linked to the fact that lateral excursions were smaller in straight lines than in bends because of road geometry. As a consequence, lateral excursions were probably judged as less risky. It can be hypothesised that the drivers not only took into consideration the expected risk, as it was manipulated by instruction, but also the 'real' risk of the situation. In straight lines, drivers were influenced by risk instructions and, as a consequence, increased their SWRS in the major risk condition. Since it was enough to bring the car back into a safe position, they had no further need to perform a larger corrective manoeuvre (as indicated by the maximum angle of the steering wheel). Furthermore, a larger corrective manoeuvre would have probably led to overshooting the targeted final position, which may even have led to an excursion into the opposite lane. So, this result may be considered as another demonstration that the drivers performed a global diagnosis of the situation, which further influenced the execution of the manoeuvre. Figure 8 illustrates these results, along with the current discussion.

In summary, most executions of the corrective manoeuvres were, at least partially, under the influence of supervisory processes. The influence of risk expectation was observed on SWRS, which was always computed during the 450 ms that followed the recording of SRT. Considering that reaction times were roughly between 300 and 500 ms, it means that the influence of symbolic processes operated around 750 ms after the assistance entered into action. Thus, drivers quickly took elements of the driving context into consideration to modulate the strength of their corrective manoeuvres.

The rationale behind the manipulation of MP strength was that a stronger input to the motor system may not facilitate the execution of the response in the direction indicated by the cue. On the contrary, it may elicit a reflexive counteraction, prompting the participants to turn the steering wheel in the wrong direction. Kullack *et al.* (2008) underlined this possibility and even proposed an assistance device, known as ReflektAS, based on this principle. The idea is that a sudden jerk of the steering wheel may tap into basic reflex circuitry, producing automatic and fast responses. Although strong MP was three times higher than light MP, our results do not show any indication that

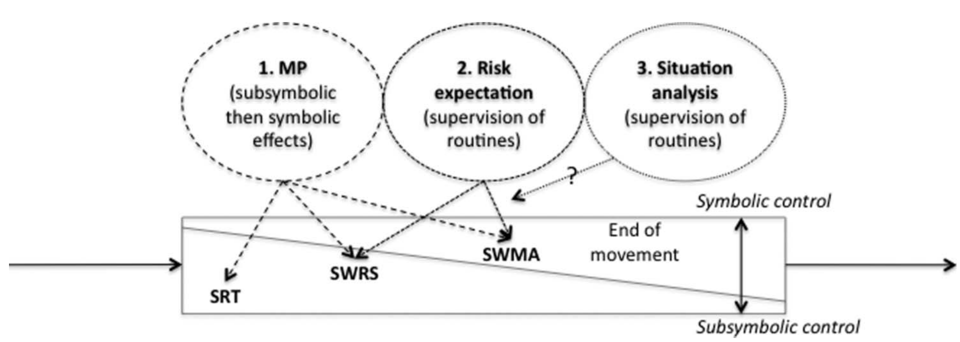

Figure 8. Illustration of results. MP has an effect on SRT (reduction), SWRS (increase) and SWMA (increase). Risk expectation has an effect on SWRS (increase) and SWMA (increase for bends only). Situation analysis seemed to modulate the effect of risk expectation on SWMA. These effects produced a reduction of the DLE in bends and in straight lines. The global pattern of results suggests that the initiation of movement was determined by subsymbolic control and that the influence of symbolic control by means of supervision of routines progressively increased during the corrective manoeuvre.

such behaviour occurred. Actually, the reduction of reaction times reported by Kullack *et al.* (2008) was replicated, but the steering response was always in the direction of the stimulation, whatever its strength. Beyond SRT, the results show that stronger MP increased SWRS and SWMA, which yielded a reduction of the DLE. This suggests that a stronger MP can improve recovery manoeuvres even better than mild motor cuing. However, Navarro *et al.* (2010) pointed out that the acceptance of an MP-based system may be impaired if the system is judged to be too intrusive. Thus, any design goals should look to achieve a system that facilitates the corrective gesture without being perceived as too intrusive in terms of vehicle control.

Finally, the potential limitations of our study should be addressed. A first possible issue is about the visual occlusion method. Visual occlusions allowed a high control of the timing and positioning of lane departure events; this was essential for assessing the effects of driving assistance and risk expectation independently of any contextual factors. However, it could be argued that the ecological validity of this method is weak and that other methods exist, such as the manipulation of lane width and density of traffic (Dijksterhuis *et al.* 2011) or distraction by means of a secondary task (Navarro *et al.* 2010). A replication with one of these methods would help to determine the extent to which the present results could be generalised. Furthermore, future studies should investigate how the effects of MP could be translated to other types of critical situations. Slippery roads, for instance, may pose a challenge. In that case, the MP cue would interact with strong modifications of steering wheel force feedback due to adherence loss.

The use of a fixed-base simulator to investigate steering responses in critical situations may also be discussed. Although the IRCCyN simulator renders very realistic steering wheel force-feedback through a real-car active steering system and advanced vehicle models, no inertial cues were present. A recent study compared loss of adherence situations in static (IRCCyN) and dynamic (Renault Ultimate) driving simulators (Denoual *et al.* 2011). The results highlighted the role of non-visual information on the subjective perception of loss of adherence, with steering wheel haptic cues predominating for the static simulator and motion platform predominating for the dynamic simulator. In both cases, the execution of the corrective response was quite similar.

Finally, subjects were instructed to keep both hands on the steering wheel and maintain the standard '10-to-2' position; in real life, however, many different hand positions can be observed. Further investigation should study how the benefits of MP could be generalised to other ways of holding the steering wheel. The benefits of a repetitive haptic cue that lasts for a period of one second, as in the present study, should also be compared with a simple jerk of the steering wheel.

Lastly, whatever the instructions given in this experiment, drivers were not really in a risky situation. It could be hypothesised that any effects of risk expectation would be greater within real driving conditions.

Conclusion

Several conclusions can be drawn from this experiment. First, our results support the hypothesis proposed by Navarro *et al.* (2007, 2010), according to which MP intervenes at a motor level, proprioceptively pre-activating the corrective gesture. Navarro and colleagues reached this conclusion on the basis of the comparison between MP and various types of LDWS. Here, another approach was chosen. We showed that reaction times were influenced by the variation of the strength of the motor cue, not by risk expectation that was induced by symbolic information. This supports the idea that the initiation of the steering response is produced at a subsymbolic level only and that MP intervenes at this level. However, it was also proven that drivers can modulate their response very early during the execution of the corrective manoeuvres in accordance with the level of perceived hazard. Beyond the question of modulation, the question of the inhibition of MP effects should also be considered in future studies (Prochazka *et al.* 2000). This corresponds to the ability of drivers to fully inhibit the effects when they disagree with the suggested corrective manoeuvre.

Finally, the present paper focuses on MP devices. However, the supervision of other types of systems that are designed to blend into the driver's sensorimotor control loop may pose very similar issues. This is particularly the case with automation based on shared control of the steering wheel (Griffiths and Gillespie 2005).

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