Transportation Research Part F 16 (2013) 92–103

Contents lists available at SciVerse ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Effect of strength and direction of haptic cueing on steering control during near lane departure

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ARTICLE INFO

Article history:
Received 3 April 2012
Received in revised form 27 August 2012
Accepted 31 August 2012

Keywords:
Haptics
Lane departure warning systems
Cognitive control
Steering behaviour

ABSTRACT

The present study compared two distinct approaches to designing driving assistance devices. These devices aim to facilitate steering responses by delivering directional pulses on the steering wheel when lane departure is imminent. In one case, the aim is to prime the corrective gesture through a haptic cue in the direction of the lane centre (motor priming). The other approach consists of eliciting a compensatory reflex reaction by means of a jerk of the steering wheel in the opposite direction. Central to this investigation are the safety benefits of the devices and the ability of drivers to remain in full control of their steering responses. The steering behaviour of 18 participants during near lane departure in bends and in straight lines was analysed. The strength and direction of haptic cueing was manipulated. The results show that drivers were always able to control the direction of the steering response when the haptic cue was delivered. No reflex counteraction was observed, whatever the strength or the direction of the stimulus. The fastest responses were observed when the cue was directed toward lane departure, especially when cueing was strong. However, these did not necessarily lead to the fastest returns to a safe position in the lane when compared with motor priming toward the lane centre. The latter yielded improved manoeuvre execution as soon as the steering movement was initiated. These results are discussed in relation to the sensorimotor and cognitive processes involved in steering behaviour. Their implications for the design of haptic-based lane departure warning systems are considered.

1. Introduction

Driving a vehicle requires constant monitoring of the trajectory. It is a fairly easy task, but it is continuous, and driving for long periods may lead to errors because of a lack of attention. One of the more serious consequences is lane departure. In 2003, out of 855,000 accidents, about a quarter that led to injury or death in Canada, France, Germany and the Netherlands have been classified as single-vehicle accidents (24%). This rises to more than one third (36%) when accidents in urban environments are excluded from the analysis (UNECE, 2007). In their extensive analysis of pre-crash scenarios in the USA, Najm, Smith, and Yanagisawa (2007) reported that road edge departure without prior vehicle manoeuvre was the second most frequent type of single light-vehicle accidents. This represented an economic cost of $8.9 billion and an estimated loss of 271,700 functional years for victims. Driving assistance devices are one solution to this problem (Hoc, Young, & Blosseville, 2009; Navarro, Mars, & Young, 2011). For example, lane departure warning systems (LDWS) aim to improve situation diagnosis by indicating to the drivers that they are getting too close to the lane border. In order not to overload the visual channel, more and more assistance devices use other sensory channels. In recent years, the haptic channel has gradually gathered

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1369-8478/$ - see front matter
http://dx.doi.org/10.1016/j.trf.2012.08.015

interest in the area of transportation research (Onimaru & Kitazaki, 2010). Various studies have shown that this could be an effective channel for conveying information to the driver (Ho, Tan, & Spence, 2006). This is the case for the accelerator pedal, which is used to assist speed control (de Rosario et al., 2010; Kuge, Boer, Yamamura, Ward, & Manser, 2006) or to promote eco-driving (Azzi, Reymond, Mérienne, & Kemeny, 2011). It also applies to the use of the steering wheel in assisting lateral control (Beruscha, Augsburg, & Manstetten, 2011; Navarro, Mars, Forzy, El-Jaafari, & Hoc, 2010; Navarro, Mars, & Hoc, 2007; Suzuki & Jansson, 2003). Assistance to lateral control can be occasional or continuous (Griffiths & Gillespie, 2005). The present study compared two distinct approaches (motor priming vs reflexive counteraction) to the design of occasional driving assistance devices aimed at facilitating steering responses in critical situations by means of directional haptic cueing.

1.1. Motor priming and cognitive control

The motor priming (MP) approach proposed by Navarro, Mars, and Hoc (2007), Navarro, Mars, Forzy, El-Jaafari, and Hoc (2010) consists in delivering fast, small and asymmetric oscillations on the steering wheel when a large deviation of lateral position is detected. Signal directionality is given by the asymmetry between a relatively shorter and stronger torque pulse toward the centre of the lane than toward the direction of lane departure. In this way, MP indicates in which direction the steering wheel should be turned, with no direct effect on the vehicle's trajectory. The increased effectiveness of MP compared to other directional warning systems has been demonstrated. Actually, Navarro et al. (2007, 2010) made a series of comparisons between MP (alone or in combination with auditory warning) and various configurations of warning systems (including directional and non-directional steering wheel vibration). In particular, the comparison between directional steering wheel vibration and MP allowed to isolate the specific role of the motor component of the MP signal in the improvement of recovery manoeuvre. Both devices were identical (i.e. they both provided directional information to the hands by means of the haptic modality), with the exception of the motor prompt, which characterises MP. Drivers were always quicker to return to a safe position with MP than with any of the other warning systems. A detailed analysis of various steering indicators revealed that this was due to an improved execution of the steering wheel corrective movement.

It has been proposed that MP improves corrective manoeuvres because it intervenes at the sensory-motor level, whereas classic warning devices only act on the decision-making process. Indeed, whatever the sensory modality through which it is perceived, any warning information is symbolic; it aims to improve the situation diagnosis. In particular, a LDWS gives information about the position of the car, with a view to faster decision-making and more rapid acting on the steering wheel. MP gives a warning to the driver, but it also acts at the proprioceptive and motor levels by pre-activating the corrective gesture. In order to put this idea in perspective, we can refer to the model developed by Parasuraman, Sheridan, and Wickens (2000), which is related to levels of automation (Fig. 1). Within this model, MP can be described as follows: it acquires information about the lateral position of the car, analyses this information relative to a safety threshold and selects the appropriate response. Then, it acts on the driver both at the level of motor control (haptic prime) and at the level of decision making (warning).

The effectiveness of MP can be interpreted within the framework of the model of cognitive control in dynamic situations proposed by Hoc and Amalberti (2007). This model is partly based on the Skill-Rule-Knowledge model introduced by Rasmussen (1986). It emphasises the distinction between symbolic control, which involves mainly interpretative processes fed by higher order information, and subsymbolic control, which encompasses perceptual and motor processes fed by sensory signals. This model clarifies the influence of supervisory processes (symbolic) on the execution of routines (subsymbolic), which was introduced by Anderson et al. (2004). Within this model, MP facilitates the initiation and early execution of the corrective manoeuvre by acting at the sensorimotor level (subsymbolic control). It also warns the driver, which improves the diagnosis of the situation at the level of symbolic control. In turn, supervisory processes can modulate the initiated motor response.

Navarro et al. (2007, 2010) first hypothesised this dual intervention of subsymbolic and symbolic control. This question has been specifically addressed by Deroo, Hoc, and Mars (2012), who showed that MP reduced reaction times of corrective

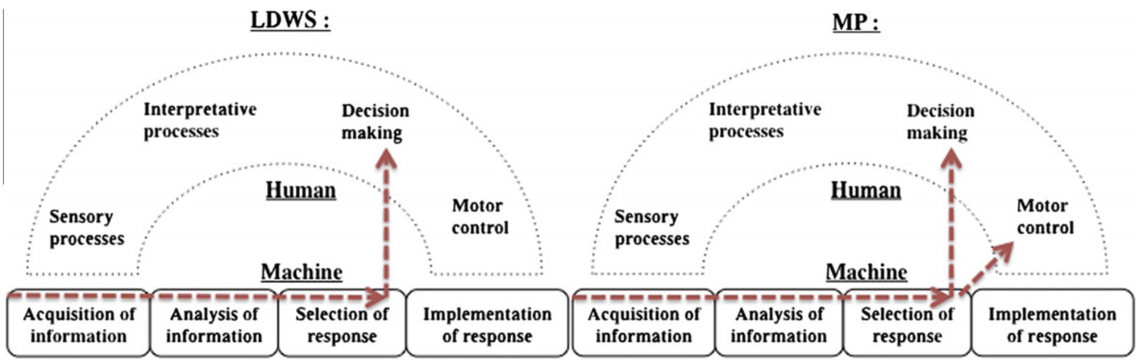

Fig. 1. Illustration of the different degrees of intervention on a driver's cognitive processes with classic LDWS and MP systems.

gestures during near lane departure. By way of contrast, the level of ‘‘risk expectation’’ manipulated by symbolic information (text messages displayed during visual occlusions) did not influence reaction times. It only influenced the strength of the corrective movements once it was initiated. This suggests that the benefits of MP are due to an early intervention at the sensory motor level (subsymbolic control), which can be modulated by symbolic situation analysis.

1.2. Motor priming vs reflexive counteraction

Some results obtained with devices delivering directional pulses on the steering wheel, such as MP, pose the question of whether the driver has the ability to fully control the response elicited by the haptic cue. Indeed, Suzuki and Jansson (2003) observed than when drivers were not informed that they would receive directional pulses on the steering wheel, half the participants followed the direction indicated by the device, while the other half of the participants steered away from it, as if the stimulus was a perturbation that needed to be counteracted. Kullack, Ehrenpfordt, Lemmer, and Eggert (2008) proposed an assistance device called ReflektAS, based on the idea that reflex reactions to steering pulses can be elicited quickly and reliably. They found very fast counteractions to strong pulses that were directed toward the side of lane departure. Hence, although MP and ReflektAS deliver pulses on the steering wheel to improve the driver’s response, they are based on two opposing principles: MP delivers mild haptic cues to the arm motor system[1] in order to indicate the direction of the required steering wheel motion, whereas ReflektAS aims to elicit a reflexive counteraction to a strong pulse in the direction of lane departure. These two approaches differ in terms of their expected influence on the driver’s behaviour (priming vs counteraction), but also in terms of how much control the driver is supposed to have over the provoked response. Indeed, it should be possible to inhibit the MP response, whereas a reflexive response should, by definition, be uncontrollable. According to Prochazka, Clarac, Loeb, Rothwell, and Wolpaw (2000), a movement is considered to be voluntary if it can be modulated or inhibited and a reflex movement if it cannot. Applied to the case of haptically cued steering responses, MP may trigger micro-myotatic reflex responses in the arms, which may be observable by means of EMG recordings, but, in terms of ergonomics, the question is to determine whether this translates as a steering wheel movement in the opposite direction that cannot be modulated or inhibited by the drivers.

1.3. Strength and direction of motor priming

When comparing the steering pulses delivered by MP and ReflektAS, some differences are apparent. On the one hand, MP delivers repetitive pulses of moderate intensity (2 N/m) in the direction of the lane centre (Navarro et al., 2010). On the other hand, Kullack, Ehrenpfordt, Lemmer, and Eggert (2008), Kullack, Ehrenpfordt, and Eggert (2010) tested different strengths of torque pulse up to 7 N/m in the direction of lane departure. Both strength and direction may be important to explain how these systems influence steering responses.

According to existing neurophysiological literature, it is difficult to evaluate the necessary magnitude of the pulse delivered on the steering wheel to elicit a compensatory reflex reaction of the arm motor system (Cooke, 1980). Nonetheless, it is reasonable to assume that the stronger the pulse, the higher the chance of yielding such a response. It can be hypothesised that pulses below the reflex threshold would be perceived as haptic cues; thus, they would indicate to the arm motor system the direction in which the movement should be executed. On the other hand, stronger pulses may trigger compensatory reflexes. In other words, increasing the strength of the haptic cue may transform MP from an incentive to act to an irrepressible response to counteract. As such, MP would intervene lower on the continuum between symbolic and subsymbolic control, at the reflex level.

With regard to the direction of the directional cue, steering responses are expected to be faster and have fewer errors when stimuli and responses correspond spatially (Guiard, 1983). Recently, Beruscha, Wang, Augsburg, and Wandke (2010) investigated whether drivers steer toward or away from vibro-tactile stimuli applied on one side of the steering wheel. The results revealed that in an abstract environment, responses were indeed faster when the haptic cue was in the same direction as the correction needing to be initiated. However, in a driving environment, faster responses were observed when target and haptic cues were in opposite directions. The authors concluded that in the context of driving, avoidance manoeuvres in response to directional stimulation on the steering wheel might be more efficient when the indicated direction is contralateral to the danger. Moreover, other laboratory studies on reaction times have shown that faster responses can be observed with primes and targets in the opposite direction when a delay is introduced between them, the so-called negative compatibility effect (Boy & Sumner, 2010; Eimer & Schlaghecken, 2003; Sumner, 2007; Wilson, Tresilian, & Schlaghecken, 2010).

1.4. Aims of the study

Taking previous arguments into consideration, it remains to find out how directional pulses should be delivered on the steering wheel with maximal efficiency to prevent lane departures. From a theoretical point of view, the question is to deter-

[1] With arm motor system, we refer to peripheral and central components of the nervous system in charge of controlling the activity of the arm muscles. This includes proprioception as well as active and passive control of muscle contraction.

mine how haptic cueing intervenes at the subsymbolic (sensorimotor) level and to what extent the driver remains in control of the corrective manoeuvres when prompted to react. To this end, the present study assessed the effects of the strength and direction of MP in lane departure situations. An improvement of corrective manoeuvres was expected when mild haptic cueing indicated the direction of the lane centre, as previously reported. The goal was to determine whether drivers could inhibit inappropriate steering response when MP was directed in the opposite direction, both with mild MP and with much stronger pulses, which may elicit fast compensatory "reflexive behaviour". In accordance with the idea that symbolic control quickly allows to take into account the context and modulate the execution of the steering response, we hypothesised that contralateral MP would not give rise to manoeuvres in an inappropriate direction, even with pulses of higher intensity. However, we expected an effect of the strength and direction of the haptic cue on steering reaction times, which seems to be mainly determined at the sensorimotor level. In particular, reduced steering reaction times may be observed with contralateral pulses. However, it may not translate as an improved action on the steering wheel and a gain in terms of safety.

2. Method

2.1. Participants

Eighteen drivers (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 systems have shown no effect of gender on the perception of haptic intensity, reaction times or the control of lateral position (Stanley, 2006). They had all held a driving licence for at least 2 years (mean = 8.6 years). Self-reported annual mileage for the past year ranged from 1000 to 35,000 km (mean = 11,000 km). The participants reported no motion sickness.

2.2. Simulator

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 force-feedback. The SCANNeRII®[2] software package was used with the CALLAS® dynamic vehicle model (Lechner, Delanne, Schaefer, & Schmitt, 1997). The visual environment was displayed on three 32-in. LCD monitors, one positioned in front of the driver and two laterals turned at 45° from the front one, viewed from a distance of about 1 m and covering 115° of visual angle in width and 25° in height. The graphics database reproduced a country environment.

2.3. Manipulated settings of motor priming

As was the case in previous studies by Navarro et al. (2007, 2010), the assistance device delivered asymmetric oscillations on the steering wheel when the car was about to cross one of the lane edges. The first movement of the steering wheel and every second movement lasted 100 ms and both movements were directed toward the road centre. In between them, weaker (0.5 N/m) and longer (200 ms) torque pulses were directed toward the opposite side. In each lane departure situation, three cycles of MP were delivered with an oscillation frequency of 3.3 Hz (Fig. 2).

Two MP settings were manipulated in the present experiment: strength (S = without assistance, light MP, strong MP), and direction (D = toward lane centre, called *ipsilateral* or toward lane departure, called *contralateral*). For light MP, the first pulse and every second pulse were set at 2 N/m. For strong MP, the pulses were three times stronger (6 N/m). Thus, light ipsilateral MP corresponded to the conditions used by Navarro et al. Light contralateral MP would be considered as an erroneous indication according to the gesture initiation logic and according to the visual scene. On the other hand, the strong contralateral MP, using torque pulses at intensities close to the highest values tested by Kullack et al. (2008), may elicit appropriate compensatory reactions toward the lane centre. On the other hand, ipsilateral strong MP might induce incorrect responses.

2.4. Procedure

Crossing the strength and the direction factors resulted in six driving situations, which were repeated four times. In fact, the conditions without assistance were identical in both the ipsilateral and contralateral conditions since the strength of MP was set to zero. However, the distinction was made in order to better control the order of presentation of the conditions. Statistical analyses respected this distinction.

The 18 drivers recruited for this experiment had participated in another experiment a few days earlier. The aim of this previous experiment was to study the influence of risk expectation on recovery manoeuvres with MP. The results were reported in Deroo et al. (2012). Thus, since drivers were already accustomed to MP and to the simulator, no familiarisation was needed this time. The present experiment lasted for 50 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] http://www.scanersimulation.com/.

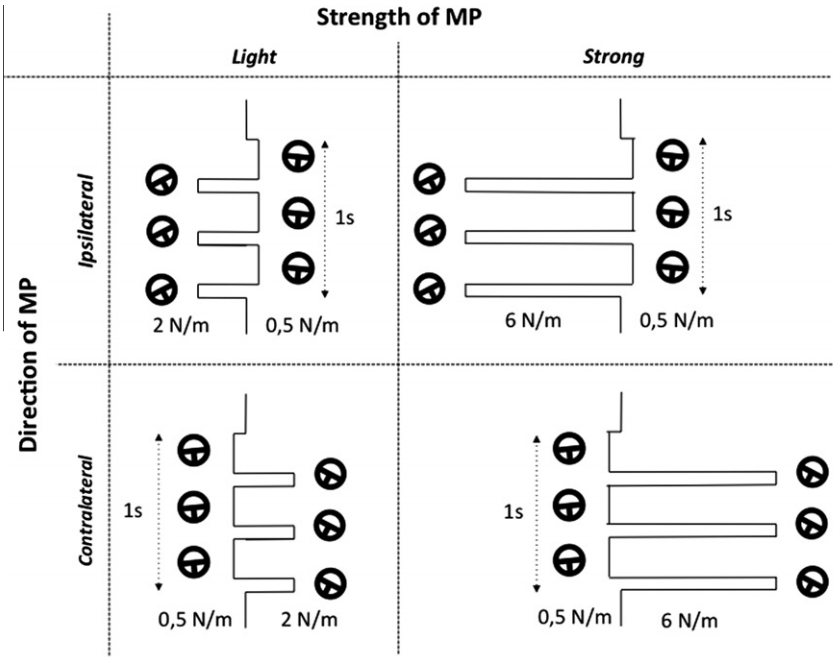

Fig. 2. Illustration of the four conditions in which MP was active during near lane departure on the right. The MP strength was either 2 N/m (light MP) or 6 N/m (strong MP). MP was oriented toward the lane centre (ipsilateral MP) or toward the side of lane departure (contralateral MP).

2'' position. This hand positioning was to be maintained throughout the experiment. Participants were instructed to drive in the right lane, as they usually would, and to respect a speed limit of 70 km/h.

In each trial, drivers drove along a 3 km country road. Each trial lasted 3 min. The road was a two-lane road with 8 straight lines and 11 bends (curve radius ranging from 70 m to 500 m), with 7 turning to the left and 4 turning to the right. The driving lane was 3 m wide and delineated with a broken centreline and an edge line. Some intersections were present and other occasional vehicles were simulated to encourage participants to remain in their own lane.

In order to assess the effects of strength and direction of MP independently of any contextual factors, it was essential to provoke very similar lane departure incidents in all situations. To this end, visual occlusions were chosen (Brookhuis, de Waard, & Fairclough, 2003). This was achieved by suddenly blacking out all screens during driving. 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. 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 (when one of the vehicle wheels crossed a virtual line situated 60 cm from the edge line): this is precisely the point at which the driving assistance device was put into action. 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 similarly large curvatures (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. Thus, they could occur at four different positions, but only two occurred randomly per lap. They were, therefore, relatively unpredictable. Although some of the participants might have learned to some extent the positions of the visual occlusions through the repetition of trials, it should be noted that the direction of lane departure remained completely unpredictable in straight lines. However, in bends, an early assessment of the bend direction might have allowed to guess the side of the lane departure. This will be addressed in the discussion.

2.5. Data analyses

Three indicators of steering performance were analysed. First, the duration of lane excursion (DLE) corresponded to the effectiveness of MP in terms of safety. It has been computed as the time spent outside the safety envelope of ±80 cm from the lane centre, after the triggering of MP. The two other variables were computed to more precisely describe the effect of MP on steering wheel control. The steering reaction time (SRT) corresponded to the time that elapsed between the triggering of the assistance device and the point at which drivers began to act on the steering wheel. Finally, the maximum steering wheel rotation speed (SWRS) was used as an indicator of the strength of the driver's motor response. It was computed during the 450 ms that follow the start of the steering response. Fig. 3 represents the relationship between all dependent variables that were analysed to assess performance.

Right bends and left bends revealed very similar patterns of results with no significant difference observed irrespective of the variable that was considered. Similarly, results for right and left departures in straight lines were qualitatively close. So, analyses were regrouped in both cases. The significance of the effects of all independent variables was assessed for DLE, SRT, SWRS by repeated measures ANOVAs with an embedded factor for the counterbalancing of orders. Dependent *t*-tests have been used for pairwise comparisons. For analyses with more than two comparisons, the quadratic means (*l*) was used. In addition, the population effects sizes were evaluated on the basis of fiducial inference. Fiducial inference (Lecoutre & Poitevineau, 2005; Rouanet, 1996; Rouanet & Lecoutre, 1983) 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 give conclusions on effect sizes with a guarantee of .90. For example "$\delta > 20$" will mean "the probability for δ being greater than 20 is .90". Paired comparisons tested the effects of the two levels of MP strength relative to the condition without assistance.

3. Results

Visual occlusions lasted 2.3 s on average in bends (SD = 0.28) and 2.1 s in straight lines (SD = 0.25). There was no significant difference in duration of occlusion between the different experimental conditions (strength × direction). All but four visual occlusions led to road departures. In those four trials, the drivers managed to steer the vehicle back toward the lane centre just before the vehicle crossed the edge line. This happened in straight lines only when MP was present (2 with light MP and 2 with strong MP).

3.1. Duration of lateral excursion (DLE)

The DLE without assistance was, on average, 2.27 s in bends and 1.9 s in straight lines. The strength (S) and the direction (D) of MP showed a significant interaction in bends and in straight lines (Table 1 and Fig. 4).

In bends, both ipsilateral MP ($\delta < -0.44$ s) and contralateral MP ($\delta < -0.17$ s) notably reduced the DLE compared to the control condition. For light MP, the difference between ipsilateral and contralateral MP was negligible ($|\delta| < 0.14$ s). However, an ipsilateral strong MP reduced the DLE significantly more than a contralateral strong MP ($\delta < -0.34$ s). Strong MP reduced DLE significantly more than light MP when it was ipsilateral ($\delta < -0.41$ s), but not when it was contralateral ($|\delta| < 0.19$ s).

In straight lines, only ipsilateral (light and strong) MP notably reduced the DLE ($\delta < -0.27$ s). Contralateral MP had no significant effect and can be described as negligible ($|\delta| < 0.14$ s). Thus, the effect of the direction is significant for both light and strong MP. The difference is notable with light MP ($\delta < -0.13$ s) and even more with strong MP ($\delta < -0.51$ s). A corollary of these results is that strong MP reduced DLE significantly more than light MP when it was ipsilateral ($\delta < -0.15$ s), but not when it was contralateral ($|\delta| < 0.27$ s).

In sum, the device reduced the DLE in bends, irregardless of the direction of MP, whereas a reduction of the DLE was observed in straight lines only with ipsilateral MP.

3.2. Steering reaction time (SRT)

The SRT without assistance was, on average, 481 ms in bends and 458 ms in straight lines. The strength (S) and the direction (D) of MP showed a significant interaction in bends and in straight lines (Table 2 and Fig. 5).

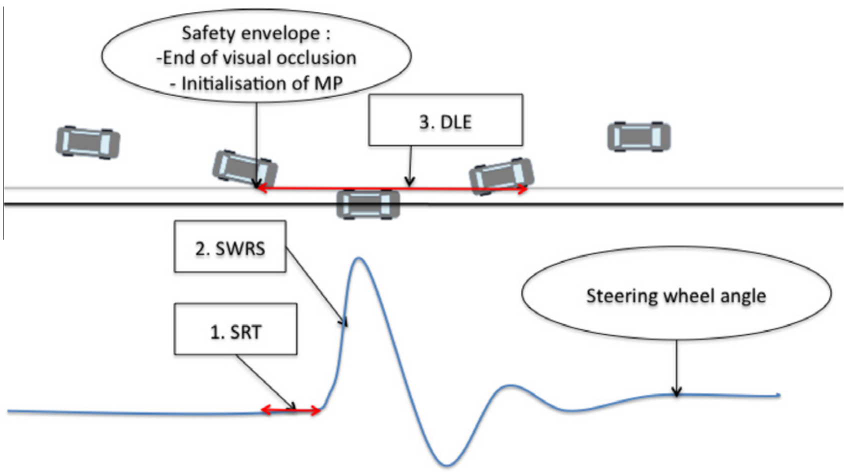

Fig. 3. The three variables. (1) Steering reaction time (SRT). (2) Maximum steering wheel rotation speed (SWRS); 3. Duration of lateral excursion (DLE).

Table 1
Analyses performed on the duration of lateral excursion (DLE), in seconds.

Variable	Comparison	*l* or *d*	Fiducial inference	Test	LoS
DLE on bends	SD	$l = 0.41$		$F(2,24) = 13.11$	$p = 0.0001^*$
	(s0 vs s1&s2) for C	$d = -0.26$	$\delta < -0.17$	$t(12) = 3.90$	$p = 0.0021^*$
	(s1 vs s2) for C	$d = -0.05$	$\lvert\delta\rvert < 0.19$	$t(12) = 0.51$	$p = 0.6168$
	(s0 vs s1&s2) for I	$d = -0.57$	$\delta < -0.44$	$t(12) = 6.10$	$p = 0.0001^*$
	(s1 vs s2) for I	$d = -0.51$	$\delta < -0.41$	$t(12) = 6.96$	$p = 0.0001^*$
	D for s1	$d = -0.01$	$\lvert\delta\rvert < 0.14$	$t(12) = 0.05$	$p = 0.9587$
	D for s2	$d = -0.46$	$\delta < -0.34$	$t(12) = 5.32$	$p = 0.0002^*$
DLE on straight lines	SD	$l = 0.47$		$F(2,24) = 23.78$	$p = 0.0001^*$
	(s0 vs s1&s2) for C	$d = 0.07$	$\lvert\delta\rvert < 0.14$	$t(12) = -1.21$	$p = 0.2479$
	(s1 vs s2) for C	$d = 0.17$	$\lvert\delta\rvert < 0.27$	$t(12) = -2.02$	$p = 0.0668$
	(s0 vs s1&s2) for I	$d = -0.38$	$\delta < -0.27$	$t(12) = 4.67$	$p = 0.0005^*$
	(s1 vs s2) for I	$d = -0.26$	$\delta < -0.15$	$t(12) = 3.22$	$p = 0.0074^*$
	D for s1	$d = -0.22$	$\delta < -0.13$	$t(12) = 3.38$	$p = 0.0027^*$
	D for s2	$d = -0.64$	$\delta < -0.51$	$t(12) = 6.55$	$p = 0.0001^*$

Note: S: strength (s0 = without assistance, s1 = light MP, s2 = strong MP); D: direction (I = ipsilateral, C = contralateral). For example, s0 vs s1&s2 for I tests the difference between the condition without assistance and the two MP conditions considered together when MP was ipsilateral.

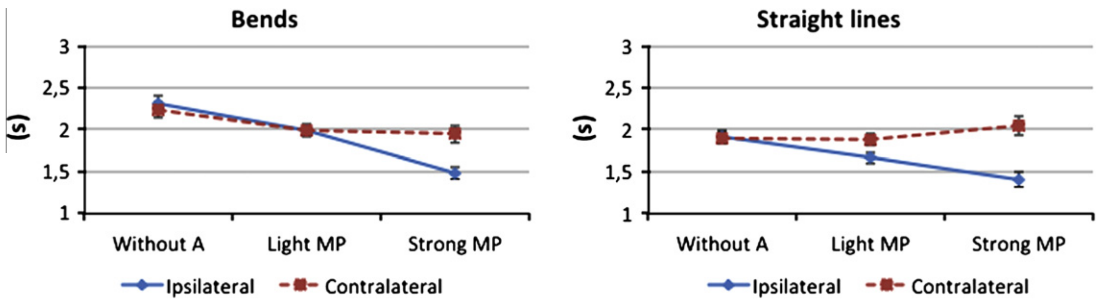

Fig. 4. Duration of lateral excursion in bends and in straight lines. Error bars represent standard errors of the means.

In bends, both ipsilateral MP ($\delta < -67.5$ ms) and contralateral MP ($\delta < -137.5$ ms) notably reduced the SRT compared with the control condition. Strong MP significantly reduced SRT more than light MP when it was ipsilateral ($\delta < -13.2$ ms) or contralateral ($\delta < -22.2$ ms). SRT with contralateral MP were significantly lower than SRT with ipsilateral MP, both for light ($\delta > 51.0$ ms) and strong MP ($\delta > 62.6$ ms).

In straight lines, only contralateral MP notably reduced the SRT ($\delta < -92.6$ ms). The effect of ipsilateral MP was non-significant and negligible ($|\delta| < 27.9$ ms). As a consequence, SRT with contralateral MP were significantly lower than SRT with ipsilateral MP, both for light ($\delta > 53.3$ ms) and strong MP ($\delta > 80.4$ ms). The difference between light and strong contralateral MP was notable ($\delta < -23.7$ ms).

Table 2
Analyses performed on the steering reaction time (SRT), in milliseconds.

Variable	Comparison	*l* or *d*	Fiducial inference	Test	LoS
SRT on bends	SD	$l = 61.4$		$F(2,24) = 13.91$	$p = 0.0001^*$
	(s0 vs s1&s2) for C	$d = -155.6$	$\delta < -137.5$	$t(12) = 11.66$	$p = 0.0001^*$
	(s1 vs s2) for C	$d = -33.3$	$\delta < -22.2$	$t(12) = 4.06$	$p = 0.0016^*$
	(s0 vs s1&s2) for I	$d = -80.6$	$\delta < -67.5$	$t(12) = 8.37$	$p = 0.0001^*$
	(s1 vs s2) for I	$d = -27.8$	$\delta < -13.2$	$t(12) = 2.58$	$p = 0.0240^*$
	D for s1	$d = 72.2$	$\delta > 51.0$	$t(12) = 4.54$	$p = 0.0001^*$
	D for s2	$d = 77.8$	$\delta > 62.6$	$t(12) = 6.95$	$p = 0.0001^*$
SRT on straight lines	SD	$l = 94.0$		$F(2,24) = 14.39$	$p = 0.0001^*$
	(s0 vs s1&s2) for dC	$d = -124.3$	$\delta < -92.6$	$t(12) = 5.32$	$p = 0.0002^*$
	(s1 vs s2) for dC	$d = -45.8$	$\delta < -23.7$	$t(12) = 2.81$	$p = 0.0158^*$
	(s0 vs s1&s2) for dI	$d = -12.5$	$\lvert\delta\rvert < 27.9$	$t(12) = 1.11$	$p = 0.2879$
	(s1 vs s2) for dI	$d = -13.9$	$\lvert\delta\rvert < 33.8$	$t(12) = 0.96$	$p = 0.3549$
	D for s1	$d = 72.2$	$\delta > 53.3$	$t(12) = 5.17$	$p = 0.0001^*$
	D for s2	$d = 104.2$	$\delta > 80.4$	$t(12) = 5.95$	$p = 0.0001^*$

Note: S: strength (s0 = without assistance, s1 = light MP, s2 = strong MP); D: direction (I = ipsilateral, C = contralateral). For example, s0 vs s1&s2 for I tests the difference between the condition without assistance and the two MP conditions considered together when MP was ipsilateral.

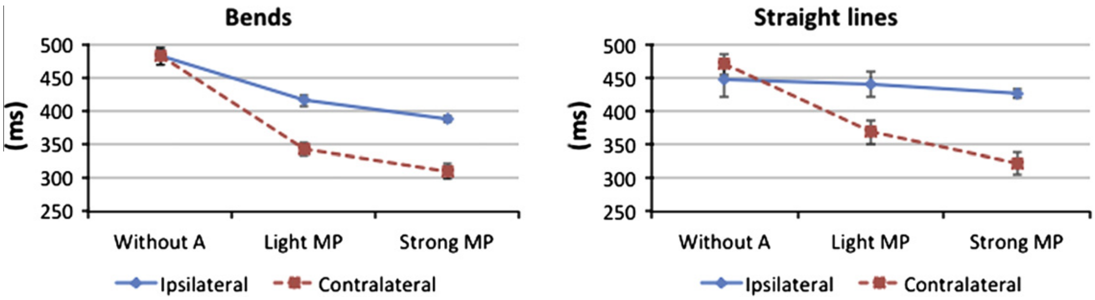

Fig. 5. Steering reaction times in bends and in straight lines. Error bars represent standard errors of means.

In sum, MP reduced SRT in bends, whatever its strength and direction, but the effect of contralateral MP was larger. In straight lines, the reduction of SRT was only observed with contralateral MP.

3.3. Steering wheel rotation speed (SWRS)

The SWRS without assistance was, on average, 201°/s in bends and 138°/s in straight lines. The strength (S) and the direction (D) of MP showed a significant interaction in straight lines but not in bends (Table 3 and Fig. 6).

In bends, both ipsilateral MP ($\delta > 62.58$°/s) and contralateral MP ($\delta > 44.8$°/s) notably increased the SWRS compared with the control condition. For light and strong MP, the difference between the ipsilateral and contralateral MP was not significant. The difference between light and strong MP was notable for ipsilateral MP ($\delta > 64.62$°/s) and contralateral MP ($\delta > 39.00$°/s).

In straight lines, both ipsilateral MP ($\delta > 80.22$°/s) and contralateral MP ($\delta > 53.4$°/) notably increased the SWRS compared with the control condition. Moreover, the SWRS was higher with ipsilateral MP than with contralateral MP for light MP ($\delta > 12.36$°/s) and for strong MP ($\delta > 18.54$°/s). The difference between light and strong MP was notable for ipsilateral MP ($\delta > 58.92$°/s) and contralateral MP ($\delta > 36.18$°/s).

In sum, MP increased the SWRS, whatever the direction, both in bends and in straight lines. The SWRT was higher in the ipsilateral condition, but this difference was only significant in straight lines.

3.4. Post-test debriefing

Post-test debriefing revealed that none of the drivers perceived that the direction of MP was manipulated. They were not aware that MP was sometimes directed away from the lane centre, even with strong MP.

4. Discussion and conclusions

The aim of the present paper was to investigate how different strengths and directions of MP determine steering behaviour during lane departure recovery. At the centre of the study was the question of drivers' ability to control the effects of MP

Table 3
Analyses performed on the steering wheel rotation speed (SWRS), in degrees per second.

Variable	Comparison	*l* or *d*	Fiducial inference	Test	LoS
SWRS on bends	SD	$l = 26.10$		$F(2,24) = 1.38$	$p = 0.2702$
	S	$l = 77.64$		$F(2,24) = 54.63$	$p = 0.0001^*$
	D	$d = -08.98$	No gen.	$t(12) = -0.96$	$p = 0.3559$
	(s0 vs s1&s2) for C	$d = 60.03$	$\delta > 44.80$	$t(12) = 5.35$	$p = 0.0002^*$
	(s1 vs s2) for C	$d = 59.72$	$\delta > 39.00$	$t(12) = 3.91$	$p = 0.0021^*$
	(s0 vs s1&s2) for I	$d = 81.08$	$\delta > 62.58$	$t(12) = 5.94$	$p = 0.0001^*$
	(s1 vs s2) for I	$d = 87.50$	$\delta > 64.62$	$t(12) = 5.19$	$p = 0.0002^*$
	D for s1	$d = -2.11$	$\|\delta\| < 10.93$	$t(12) = -0.36$	$p = 0.7229$
	D for s2	$d = 29.89$	No gen.	$t(12) = 1.21$	$p = 0.2479$
SWRS on straight lines	SD	$l = 31.81$		$F(2,24) = 3.94$	$p = 0.0330^*$
	(s0 vs s1&s2) for C	$d = 62.36$	$\delta > 53.43$	$t(12) = 9.47$	$p = 0.0001^*$
	(s1 vs s2) for C	$d = 55.17$	$\delta > 36.18$	$t(12) = 3.94$	$p = 0.0020^*$
	(s0 vs s1&s2) for I	$d = 97.31$	$\delta > 80.22$	$t(12) = 7.72$	$p = 0.0001^*$
	(s1 vs s2) for I	$d = 75.06$	$\delta > 58.92$	$t(12) = 6.31$	$p = 0.0001^*$
	D for s1	$d = 24.17$	$\delta > 12.36$	$t(12) = 2.78$	$p = 0.0168^*$
	D for s2	$d = 44.06$	$\delta > 18.54$	$t(12) = 2.34$	$p = 0.0373^*$

Note: S: strength (s0 = without assistance, s1 = light MP, s2 = strong MP); D: direction (I = ipsilateral, C = contralateral). For example, s0 vs s1&s2 for I tests the difference between the condition without assistance and the two MP conditions considered together when MP was ipsilateral.

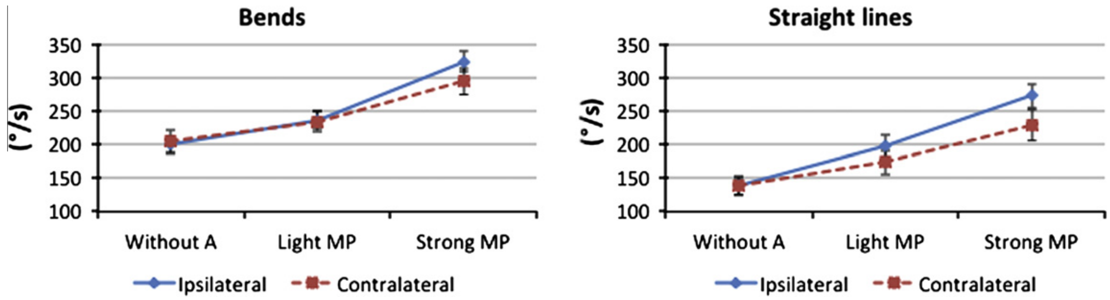

Fig. 6. Maximum steering wheel rotation speed in bends and in straight lines. Error bars represent standard errors of means.

when directional pulses are delivered on the steering wheel. In summary, the results confirm that light ipsilateral MP, as originally proposed by Navarro et al. (2007), reduces the duration of lateral excursion. This is due to a small reduction in steering reaction times and an increase in steering wheel rotation speed. This pattern of results was also observed, and could even be seen to have increased, when ipsilateral MP delivered steering pulses of much higher intensity. Thus, no compensatory reaction was observed. When contralateral MP was used, a larger reduction in steering reaction times was observed. However, the execution of the corrective response was not as efficient as with ipsilateral MP, as attested by a significantly smaller reduction in lane departure duration. The following discussion will first address the question of the nature of the MP-induced response, excluding the hypothesis of a compensatory reflex reaction to the steering pulses. The role of the symbolic processes in the determination of the response will also be considered. Then, we will specifically discuss the reduction of SRT with contralateral MP. Finally, we will address some potential limitations of the study and conclude in terms of ergonomics and safety recommendations.

4.1. Initialization of the correction vs compensatory reaction

In all cases, drivers turned the steering wheel in the appropriate direction, whatever the strength or direction of MP. This demonstrates that the drivers always took into account the visually perceived driving context when orienting their steering wheel movement. This contrasts with the results of Suzuki and Jansson (2003) in which frequent errors were reported. It should be noted however that those erroneous responses could be attributed to a lack of information to the participants. The frequency of errors drastically diminished when the drivers were informed that pulses on the steering wheel would be delivered. It may also be explained by the difference between the simple pulses used by Suzuki and Jansson (2003) and the asymmetric bidirectional pulses of MP. Nevertheless, it was legitimate to ask whether MP-induced response could be inhibited, for example in cases of system error. Furthermore, on the basis of an observed reduction of reaction times, Kullack et al. (2008) proposed that a jerk of the steering wheel in the direction of lane departure may elicit a more efficient reflex response in the opposite direction. Our results do not support this idea. MP might have elicited small myotatic reflex responses in the arms, which could not be observed without any EMG recording, but it did not give rise to inappropriate steering responses. The steering wheel movements, even with pulses of high intensity, were always a function of the visually perceived situation, even very early in their execution. In that sense, the responses we observed cannot be considered as involuntary steering responses to a haptic stimulus.

Besides, this study demonstrated that MP should not be reduced to its effects on reaction times. It is essential to consider the whole correction manoeuvre to evaluate benefits in terms of safety. Even though ipsilateral MP did not reduce SRT as much as contralateral MP, it gave rise to sharper responses, as seen on the SWRS, and in the reduced time spent in a dangerous lateral position. Thus, it is clearly apparent that MP helped to initiate and execute the corrective gesture. Furthermore, considering that a reduction of the DLE is the most important indicator of safety improvement, orienting the steering pulses in the expected direction of movement is the best strategy for the design of such devices. In a case of erroneous indication, consequences may not be critical, since the direction of the response seemed to be always determined in accordance with the analysis of the driving context. In other words, the supervision of routines rapidly became efficient. This is in line with the observations reported by Deroo et al. (2012), who showed that risk expectation (processed at the symbolic level) could be evidenced on SWRS very early during the response execution. However, they found no effect of risk expectation on SRT, which suggests that this movement parameter mainly depends on subsymbolic control.

4.2. Effect on steering reaction times with contralateral MP

Ipsilateral MP only marginally improved SRT. The reduction was small in bends and negligible in straight lines. By contrast, contralateral MP markedly accelerated the drivers' responses. Thus, the drivers did more than just inhibit the responses suggested by contralateral MP. They countered the device when it indicated the wrong direction, with even shorter reaction times than with ipsilateral MP. In that sense, the results reported by Kullack et al. (2008) were replicated. However, they cannot be attributed to the reflexive nature of the response since the direction of the response was in full voluntary control, i.e. the direction of the stimulus only did not determine the direction of the response. The question remains to know why SRT, which were shown to be unaffected by symbolic control (Deroo et al., 2012), were smaller with contralateral MP. It could be the case that as soon as the visual occlusion ended, drivers immediately perceived a mismatch between their vision of the vehicle's motion (heading outside the lane) and the direction of the haptic cue (prompting the hand to steer the vehicle even further in the wrong direction). It can be hypothesised that this sensory mismatch was processed at the subsymbolic level and gave rise to a faster response than when MP was compatible with visual information. It might be considered as an equivalent to the so-called negative compatibility effect. In laboratory settings, shorter reaction times are usually observed when a delay (typically 150 ms) is introduced between a subliminal prime (an early indication of the direction of the expected response) and the target (Boy & Sumner, 2010; Eimer & Schlaghecken, 2003; Sumner, 2007; Wilson et al., 2010). Driving a car is obviously a much more complex task than the previous paradigm. However, the time needed to process visual information on the car heading may correspond to the delay between priming and decision-making typically associated with negative compatibility effects. Obviously, this interpretation is quite speculative and further experiments should be conducted to test it.

4.3. Limitations of the study

This study presents some potential limitations that will be addressed now. First, the visual occlusion method was chosen because it allowed experimental control of the timing and positioning of lane departure events. This was essential in order to assess the effects of MP strength and direction independently of any contextual factors. This goal has been achieved as almost all occlusions led to road departure without loss of control. However, it could be argued that the ecological validity of this method is weak and that other methods exist, such as the introduction of a secondary task to distract the driver. As a matter of fact, Navarro and colleagues showed very comparable results when studying MP and other lane departure warning systems using visual occlusions (Navarro et al., 2007) and a secondary task (Navarro et al., 2010), although distraction gave rise to more variability in the severity of lane departures. Still, visual occlusions occurred repeatedly and it could be argued the drivers learned to monitor the driving environment in order to prepare themselves for the moment the scene disappeared. This cannot be excluded and raises the issue of lane departure predictability. Although visual occlusions did not occur at the same road positions across trials, we cannot exclude that the drivers learned their positions to some extent by the end of the experiment. However, that does not make the consequence of the occlusion predictable, at least not in straight lines, since, in that case, the direction of lane departure varied for a given position. In bends, if the participant was carefully monitoring the driving scene before the occlusion, he or she might have determined the direction of the upcoming bend and the appropriate response to execute. Then again, this was the case in all conditions, in which differences in terms of safety improvement were observed.

As mentioned in the procedure, all drivers in the present study had already participated to another experiment on MP (Deroo et al., 2012). In that experiment, the participants experienced light and strong MP like in the present study, but MP was always ipsilateral. One could legitimately wonder whether that previous experience created a familiarisation to ipsilateral MP, which might make the comparison with contralateral MP difficult. However, it is important to note that these experiments were not conducted in close succession. The time between the experiments varied across participants between 4 and 10 days. Moreover, if the drivers had actually been trained to respond in the direction of the haptic cue, the first exposure to contralateral MP would most probably have been yielded inappropriate responses, such as steering in the wrong direction. Following those first trials with contralateral MP, the drivers would have learned that MP was not always ipsilateral and the difference between ipsilateral and contralateral MP should have quickly disappeared. However, we did not observe such a pattern of result. Thus, the presence of the previous experiment can hardly explain the observed difference between the two directions of MP.

5. Conclusions and ergonomics recommendations

This study confirmed that driving assistance devices that deliver torque pulses on the steering wheel can markedly improve the execution of recovery manoeuvres during lane departure episodes. It was established that the response consecutive to the device action always remained under the control of symbolic processes and could not be considered as reflexive, even when steering pulses were quite strong. The fastest reaction times were observed with strong contralateral pulses. However, these did not translate into increased safety benefits. Hence, a reduction in reaction times should not be an objective per se. Our results support the MP principle, according to which haptic cues delivered on the steering wheel should aim at indicating to the arm motor system the direction of the movement to be executed. The motor system may improve reaction times, but also, and more importantly, the early execution of the corrective manoeuvre.

Although increasing the strength of ipsilateral MP yielded shorter duration of lane excursion, it should not be concluded from this study that pulses of 6 N/m or higher need to be used. Navarro et al. (2010) compared the acceptance of MP and other lane departure warning systems after repetitive exposure to them. In general, the acceptance of all systems was poor, most probably due the frequency of intervention of the devices. However, it should be noted that, even though MP delivered mild steering pulses, drivers judged it as more intrusive and therefore less acceptable. Although it remains to be tested, it is likely that a stronger intervention would be even more rejected. On the other hand, this kind of device may be designed only for situations that become so critical an emergency response is required. If the automation intervention is restricted to these rare occurrences, the strength of the haptic cue may be set higher, with efficiency being sought more than acceptance. It could be argued, however, that fully automated countermeasures are preferable to trying to influence the behaviour of drivers in very critical situations.

Finally, it may be wise to calibrate the device action as a function of the level of attention or vigilance. MP was originally designed for situations in which the driver is distracted, but in full possession of his senses. This raises the question of how a drowsy driver (for example, drunk or sleepy) would respond to the unexpected action of an MP-like device, something that should be investigated.

Acknowledgement

This research was supported by the ANR-VTT: PARTAGE Project 0866C0222.

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