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

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49 In their extensive analysis of pre-crash scenarios in the USA, Najm et al. (2007) reported that  
50 road edge departure without prior vehicle manoeuvre was the second most frequent type of  
51 single light-vehicle accidents. This represented an economic cost of \$8.9 billion and an  
52 estimated loss of 271700 functional years for victims. Driving assistance devices are one  
53 solution to this problem (Hoc, Young & Blosseville, 2009, Navarro, Mars & Young, 2011).  
54 For example, lane departure warning systems (LDWS) aim to improve situation diagnosis by  
55 indicating to the drivers that they are getting too close to the lane border. In order not to  
56 overload the visual channel, more and more assistance devices use other sensory channels. In  
57 recent years, the haptic channel has gradually gathered interest in the area of transportation  
58 research (Onimaru & Kitazaki, 2010). Various studies have shown that this could be an  
59 effective channel for conveying information to the driver (Ho, Reed & Spence, 2006). This is  
60 the case for the accelerator pedal, which is used to assist speed control (Kuge et al. 2006; de  
61 Rosario et al. 2010) or to promote eco-driving (Azzi, Reymond, Mérienne & Kemeny, 2011).  
62 It also applies to the use of the steering wheel in assisting lateral control (Beruscha, Augsburg  
63 & Manstetten, 2011; Navarro, Mars & Hoc, 2007, 2010; Suzuki & Jansson, 2003). Assistance  
64 to lateral control can be occasional or continuous (Griffiths & Gillespie, 2004). The present  
65 study compared two distinct approaches (motor priming versus reflexive counteraction) to the  
66 design of occasional driving assistance devices aimed at facilitating steering responses in  
67 critical situations by means of directional haptic cueing.

### 68 *1.1. Motor priming and cognitive control*

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

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

97 acts on the driver both at the level of motor control (haptic prime) and at the level of decision  
98 making (warning).

99

100 < INSERT FIGURE 1 HERE >

101

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

113 Navarro et al. (2007, 2010) first hypothesized this dual intervention of subsymbolic and  
114 symbolic control. This question has been specifically addressed by Deroo, Hoc and Mars  
115 (2012), who showed that MP reduced reaction times of corrective gestures during near lane  
116 departure. By way of contrast, the level of “risk expectation” manipulated by symbolic  
117 information (text messages displayed during visual occlusions) did not influence reaction  
118 times. It only influenced the strength of the corrective movements once it was initiated. This  
119 suggests that the benefits of MP are due to an early intervention at the sensory motor level  
120 (subsymbolic control), which can be modulated by symbolic situation analysis.

121

### *1.2. Motor priming versus reflexive counteraction*

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

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<sup>1</sup> 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.

143 may be observable by means of EMG recordings, but, in terms of ergonomics, the question is  
144 to determine whether this translates as a steering wheel movement in the opposite direction  
145 that cannot be modulated or inhibited by the drivers.

### 146 *1.3. Strength and direction of motor priming*

147 When comparing the steering pulses delivered by MP and ReflektAS, some differences are  
148 apparent. On the one hand, MP delivers repetitive pulses of moderate intensity (2 N/m) in the  
149 direction of the lane centre (Navarro et al. 2010). On the other hand, Kullack et al. (2008,  
150 2010) tested different strengths of torque pulse up to 7 N/m in the direction of lane departure.  
151 Both strength and direction may be important to explain how these systems influence steering  
152 responses.

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

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

### 177 *1.4. Aims of the study*

178 Taking previous arguments into consideration, it remains to find out how directional pulses  
179 should be delivered on the steering wheel with maximal efficiency to prevent lane departures.  
180 From a theoretical point of view, the question is to determine how haptic cueing intervenes at  
181 the subsymbolic (sensorimotor) level and to what extent the driver remains in control of the  
182 corrective manoeuvres when prompted to react. To this end, the present study assessed the  
183 effects of the strength and direction of MP in lane departure situations. An improvement of  
184 corrective manoeuvres was expected when mild haptic cueing indicated the direction of the  
185 lane centre, as previously reported. The goal was to determine whether drivers could inhibit  
186 inappropriate steering response when MP was directed in the opposite direction, both with  
187 mild MP and with much stronger pulses, which may elicit fast compensatory “reflexive  
188 behaviour”. In accordance with the idea that symbolic control quickly allows to take into  
189 account the context and modulate the execution of the steering response, we hypothesised that

190 contralateral MP would not give rise to manoeuvres in an inappropriate direction, even with  
191 pulses of higher intensity. However, we expected an effect of the strength and direction of the  
192 haptic cue on steering reaction times, which seems to be mainly determined at the  
193 sensorimotor level. In particular, reduced steering reaction times may be observed with  
194 contralateral pulses. However, it may not translate as an improved action on the steering  
195 wheel and a gain in terms of safety.  
196

## 197 **2. Method**

### 198 *2.1. Participants*

199 Eighteen drivers (14 males, 4 females, 27 years of age on average) participated in the study.  
200 Gender was not balanced since previous studies on the effect of haptic collision avoidance  
201 systems have shown no effect of gender on the perception of haptic intensity, reaction times  
202 or the control of lateral position (Stanley, 2006). They had all held a driving licence for at  
203 least 2 years (mean = 8.6 years). Self-reported annual mileage for the past year ranged from  
204 1000 to 35 000 km (mean = 11 000 km). The participants reported no motion sickness.

### 205 *2.2. Simulator*

206 The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with  
207 full instrumentation. It was equipped with an active steering system for realistic force-  
208 feedback. The SCANNeR<sup>2</sup> software package was used with the CALLAS<sup>®</sup> dynamic  
209 vehicle model (Lechner et al. 1997). The visual environment was displayed on three 32-inch  
210 LCD monitors, one positioned in front of the driver and two laterals turned at 45° from the  
211 front one, viewed from a distance of about 1 metre and covering 115° of visual angle in width  
212 and 25° in height. The graphics database reproduced a country environment.

### 213 *2.3. Manipulated settings of motor priming*

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

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

232 < INSERT FIGURE 2 HERE >  
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#### 234 2.4. Procedure

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

240 The 18 drivers recruited for this experiment had participated in another experiment a few days  
241 earlier. The aim of this previous experiment was to study the influence of risk expectation on  
242 recovery manoeuvres with MP. The results were reported in Deroo et al. (2012). Thus, since  
243 drivers were already accustomed to MP and to the simulator, no familiarisation was needed  
244 this time. The present experiment lasted for 50 minutes. First, participants were asked to  
245 adjust the seat position so as to achieve a realistic and pleasant driving posture. They were  
246 asked to hold the steering wheel with both hands, in the “10-to-2” position. This hand  
247 positioning was to be maintained throughout the experiment. Participants were instructed to  
248 drive in the right lane, as they usually would, and to respect a speed limit of 70 km/h.

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

255 In order to assess the effects of strength and direction of MP independently of any contextual  
256 factors, it was essential to provoke very similar lane departure incidents in all situations. To  
257 this end, visual occlusions were chosen (Brookhuis et al. 2003). This was achieved by  
258 suddenly blacking out all screens during driving. When visual occlusion occurred,  
259 participants were asked to stop making adjustments to steering. Thus, visual occlusions that  
260 occurred when entering bends caused a natural lane departure. In order to standardize the  
261 direction of lane departure in straight lines, a slight and imperceptible shift in the vehicle  
262 heading was introduced when the visual occlusion occurred. Drivers recovered vision when  
263 lane departure was imminent (when one of the vehicle wheels crossed a virtual line situated  
264 60 cm from the edge line): this is precisely the point at which the driving assistance device  
265 was put into action. Experimental scenarios were structured in such a way that no oncoming  
266 vehicle was present just before and after a visual occlusion. Two occlusions were positioned  
267 in bends of similarly large curvatures (300 m on the left bend and 225 m on the right bend),  
268 one leading to lane departure to the right, the other to the left. The others took place in straight  
269 lines, also in two directions. Thus, they could occur at four different positions, but only two  
270 occurred randomly per lap. They were, therefore, relatively unpredictable. Although some of  
271 the participants might have learned to some extent the positions of the visual occlusions  
272 through the repetition of trials, it should be noted that the direction of lane departure remained  
273 completely unpredictable in straight lines. However, in bends, an early assessment of the bend  
274 direction might have allowed to guess the side of the lane departure. This will be addressed in  
275 the discussion.

#### 276 2.5. Data analyses

277 Three indicators of steering performance were analyzed. First, the duration of lane excursion  
278 (DLE) corresponded to the effectiveness of MP in terms of safety. It has been computed as

279 the time spent outside the safety envelope of  $\pm 80$  cm from the lane centre, after the triggering  
 280 of MP. The two other variables were computed to more precisely describe the effect of MP on  
 281 steering wheel control. The steering reaction time (SRT) corresponded to the time that elapsed  
 282 between the triggering of the assistance device and the point at which drivers began to act on  
 283 the steering wheel. Finally, the maximum steering wheel rotation speed (SWRS) was used as  
 284 an indicator of the strength of the driver's motor response. It was computed during the 450 ms  
 285 that follow the start of the steering response. Figure 5 represents the relationship between all  
 286 dependent variables that were analyzed to assess performance.

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289 < INSERT FIGURE 3 HERE >

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291 Right bends and left bends revealed very similar patterns of results with no significant  
 292 difference observed irrespective of the variable that was considered. Similarly, results for  
 293 right and left departures in straight lines were qualitatively close. So, analyses were regrouped  
 294 in both cases. The significance of the effects of all independent variables was assessed for  
 295 DLE, SRT, SWRS by repeated measures ANOVAs with an embedded factor for the  
 296 counterbalancing of orders. Dependent t-tests have been used for pairwise comparisons. For  
 297 analyses with more than two comparisons, the quadratic means ( $l$ ) was used. In addition, the  
 298 population effects sizes were evaluated on the basis of fiducial inference. Fiducial inference  
 299 (Rouanet and Lecoutre 1983, Rouanet 1996, Lecoutre and Poitevineau 2005) is a variant of  
 300 Bayesian statistical inference, aimed at concluding on the population effect size ( $\delta$ ) on the  
 301 basis of the observed effect ( $d$ ), the sample size and variability. It goes beyond the test of  
 302 significance, which only concludes in terms of the existence of a non-null effect. In this paper,  
 303 we will give conclusions on effect sizes with a guarantee of .90. For example " $\delta > 20$ " will  
 304 mean "the probability for  $\delta$  being greater than 20 is .90". Paired comparisons tested the effects  
 305 of the two levels of MP strength relative to the condition without assistance.

### 306 3. Results

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

#### 313 3.1. Duration of Lateral Excursion (DLE)

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315 < INSERT FIGURE 4 HERE >

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317 **Table 1 - Analyses performed on the Duration of Lateral excursion (DLE), in seconds**

Variable	Comparison	l or d	Fiducial inference	Test	LoS
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<b>DLE on bends</b>	S.D	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	$ \delta  < 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	$ \delta  < 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*
<b>DLE on straight lines</b>	S.D	l=0.47		F(2,24)=23.78	p=0.0001*
	(s0 vs s1&s2) for C	d=0.07	$ \delta  < 0.14$	t(12)=-1.21	p=0.2479
	(s1 vs s2) for C	d=0.17	$ \delta  < 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*

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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.

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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.

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### 3.2. Steering Reaction Time (SRT)

< INSERT FIGURE 5 HERE >

**Table 2 - Analyses performed on the Steering Reaction Time (SRT), in milliseconds**

Variable	Comparison	l or d	Fiducial inference	Test	LoS
<b>SRT on bends</b>	S.D	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*

<b>SRT on straight lines</b>	S.D	l=94.0		F(2,24)=14.39	<b>p=0.0001*</b>
	(s0 vs s1&s2) for dC	d=-124.3	$\delta < -92.6$	t(12)=5.32	<b>p=0.0002*</b>
	(s1 vs s2) for dC	d=-45.8	$\delta < -23.7$	t(12)=2.81	<b>p=0.0158*</b>
	(s0 vs s1&s2) for dI	d=-12.5	$ \delta  < 27.9$	t(12)=1.11	p=0.2879
	(s1 vs s2) for dI	d=-13.9	$ \delta  < 33.8$	t(12)=0.96	p=0.3549
	D for s1	d=72.2	$\delta > 53.3$	t(12)=5.17	<b>p=0.0001*</b>
	D for s2	d=104.2	$\delta > 80.4$	t(12)=5.95	<b>p=0.0001*</b>

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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.

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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).

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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).

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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).

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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.

366

### 3.3. Steering Wheel Rotation Speed (SWRS)

367

< INSERT FIGURE 6 HERE >

368

369

370

**Table 3 - Analyses performed on the Steering Wheel Rotation Speed (SWRS), in degrees per second**

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

371

372 Note: S: strength (s0=without assistance, s1=light MP, s2=strong MP); D: direction (I=ipsilateral,  
373 C=contralateral). For example, s0 vs s1&s2 for I tests the difference between the condition without assistance  
374 and the two MP conditions considered together when MP was ipsilateral.  
375

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

379 In bends, both ipsilateral MP ( $\delta > 62.58^\circ/\text{s}$ ) and contralateral MP ( $\delta > 44.8^\circ/\text{s}$ ) notably increased  
380 the SWRS compared with the control condition. For light and strong MP, the difference  
381 between the ipsilateral and contralateral MP was not significant. The difference between light  
382 and strong MP was notable for ipsilateral MP ( $\delta > 64.62^\circ/\text{s}$ ) and contralateral MP ( $\delta > 39.00^\circ/\text{s}$ ).  
383 In straight lines, both ipsilateral MP ( $\delta > 80.22^\circ/\text{s}$ ) and contralateral MP ( $\delta > 53.4^\circ/\text{s}$ ) notably  
384 increased the SWRS compared with the control condition. Moreover, the SWRS was higher  
385 with ipsilateral MP than with contralateral MP for light MP ( $\delta > 12.36^\circ/\text{s}$ ) and for strong MP  
386 ( $\delta > 18.54^\circ/\text{s}$ ). The difference between light and strong MP was notable for ipsilateral MP  
387 ( $\delta > 58.92^\circ/\text{s}$ ) and contralateral MP ( $\delta > 36.18^\circ/\text{s}$ ).

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

### 391 *3.4. Post-test debriefing*

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

## 395 **4. Discussion and conclusions**

396 The aim of the present paper was to investigate how different strengths and directions of MP  
397 determine steering behaviour during lane departure recovery. At the centre of the study was  
398 the question of drivers' ability to control the effects of MP when directional pulses are  
399 delivered on the steering wheel. In summary, the results confirm that light ipsilateral MP, as  
400 originally proposed by Navarro et al. (2007), reduces the duration of lateral excursion. This is  
401 due to a small reduction in steering reaction times and an increase in steering wheel rotation  
402 speed. This pattern of results was also observed, and could even be seen to have increased,  
403 when ipsilateral MP delivered steering pulses of much higher intensity. Thus, no  
404 compensatory reaction was observed. When contralateral MP was used, a larger reduction in  
405 steering reaction times was observed. However, the execution of the corrective response was  
406 not as efficient as with ipsilateral MP, as attested by a significantly smaller reduction in lane  
407 departure duration. The following discussion will first address the question of the nature of  
408 the MP-induced response, excluding the hypothesis of a compensatory reflex reaction to the  
409 steering pulses. The role of the symbolic processes in the determination of the response will  
410 also be considered. Then, we will specifically discuss the reduction of SRT with contralateral  
411 MP. Finally, we will address some potential limitations of the study and conclude in terms of  
412 ergonomics and safety recommendations.

### 413 *4.1. Initialization of the correction versus compensatory reaction*

414 In all cases, drivers turned the steering wheel in the appropriate direction, whatever the  
415 strength or direction of MP. This demonstrates that the drivers always took into account the  
416 visually perceived driving context when orienting their steering wheel movement. This

417 contrasts with the results of Suzuki and Jansson (2003) in which frequent errors were  
418 reported. It should be noted however that those erroneous responses could be attributed to a  
419 lack of information to the participants. The frequency of errors drastically diminished when  
420 the drivers were informed that pulses on the steering wheel would be delivered. It may also be  
421 explained by the difference between the simple pulses used by Suzuki and Jansson (2003) and  
422 the asymmetric bidirectional pulses of MP. Nevertheless, it was legitimate to ask whether  
423 MP-induced response could be inhibited, for example in cases of system error. Furthermore,  
424 on the basis of an observed reduction of reaction times, Kullack et al. (2008) proposed that a  
425 jerk of the steering wheel in the direction of lane departure may elicit a more efficient reflex  
426 response in the opposite direction. Our results do not support this idea. MP might have  
427 elicited small myotatic reflex responses in the arms, which could not be observed without any  
428 EMG recording, but it did not give rise to inappropriate steering responses. The steering  
429 wheel movements, even with pulses of high intensity, were always a function of the visually  
430 perceived situation, even very early in their execution. In that sense, the responses we  
431 observed cannot be considered as involuntary steering responses to a haptic stimulus.  
432 Besides, this study demonstrated that MP should not be reduced to its effects on reaction  
433 times. It is essential to consider the whole correction manoeuvre to evaluate benefits in terms  
434 of safety. Even though ipsilateral MP did not reduce SRT as much as contralateral MP, it  
435 gave rise to sharper responses, as seen on the SWRS, and in the reduced time spent in a  
436 dangerous lateral position. Thus, it is clearly apparent that MP helped to initiate and execute  
437 the corrective gesture. Furthermore, considering that a reduction of the DLE is the most  
438 important indicator of safety improvement, orienting the steering pulses in the expected  
439 direction of movement is the best strategy for the design of such devices. In a case of  
440 erroneous indication, consequences may not be critical, since the direction of the response  
441 seemed to be always determined in accordance with the analysis of the driving context. In  
442 other words, the supervision of routines rapidly became efficient. This is in line with the  
443 observations reported by Deroo et al. (2012), who showed that risk expectation (processed at  
444 the symbolic level) could be evidenced on SWRS very early during the response execution.  
445 However, they found no effect of risk expectation on SRT, which suggests that this  
446 movement parameter mainly depends on subsymbolic control.

#### 447 *4.2. Effect on steering reaction times with contralateral MP*

448 Ipsilateral MP only marginally improved SRT. The reduction was small in bends and  
449 negligible in straight lines. By contrast, contralateral MP markedly accelerated the drivers'  
450 responses. Thus, the drivers did more than just inhibit the responses suggested by  
451 contralateral MP. They countered the device when it indicated the wrong direction, with even  
452 shorter reaction times than with ipsilateral MP. In that sense, the results reported by Kullack  
453 et al. (2008) were replicated. However, they cannot be attributed to the reflexive nature of the  
454 response since the direction of the response was in full voluntary control, i.e the direction of  
455 the stimulus only did not determine the direction of the response. The question remains to  
456 know why SRT, which were shown to be unaffected by symbolic control (Deroo et al. 2012),  
457 were smaller with contralateral MP. It could be the case that as soon as the visual occlusion  
458 ended, drivers immediately perceived a mismatch between their vision of the vehicle's motion  
459 (heading outside the lane) and the direction of the haptic cue (prompting the hand to steer the  
460 vehicle even further in the wrong direction). It can be hypothesized that this sensory  
461 mismatch was processed at the subsymbolic level and gave rise to a faster response than when  
462 MP was compatible with visual information. It might be considered as an equivalent to the so-  
463 called negative compatibility effect. In laboratory settings, shorter reaction times are usually  
464 observed when a delay (typically 150 ms) is introduced between a subliminal prime (an early  
465 indication of the direction of the expected response) and the target (Boy & Summer, 2010;

466 Eimer & Schlaghecken, 2003; Sumner, 2007; Wilson, Tresilian & Schlaghecken, 2010).  
467 Driving a car is obviously a much more complex task than the previous paradigm. However,  
468 the time needed to process visual information on the car heading may correspond to the delay  
469 between priming and decision-making typically associated with negative compatibility  
470 effects. Obviously, this interpretation is quite speculative and further experiments should be  
471 conducted to test it.

#### 472 *4.3. Limitations of the study*

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

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

#### 508 **5. Conclusions and ergonomics recommendations**

509 This study confirmed that driving assistance devices that deliver torque pulses on the steering  
510 wheel can markedly improve the execution of recovery manoeuvres during lane departure  
511 episodes. It was established that the response consecutive to the device action always

512 remained under the control of symbolic processes and could not be considered as reflexive,  
513 even when steering pulses were quite strong. The fastest reaction times were observed with  
514 strong contralateral pulses. However, these did not translate into increased safety benefits.  
515 Hence, a reduction in reaction times should not be an objective per se. Our results support the  
516 MP principle, according to which haptic cues delivered on the steering wheel should aim at  
517 indicating to the arm motor system the direction of the movement to be executed. The motor  
518 system may improve reaction times, but also, and more importantly, the early execution of the  
519 corrective manoeuvre.

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

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

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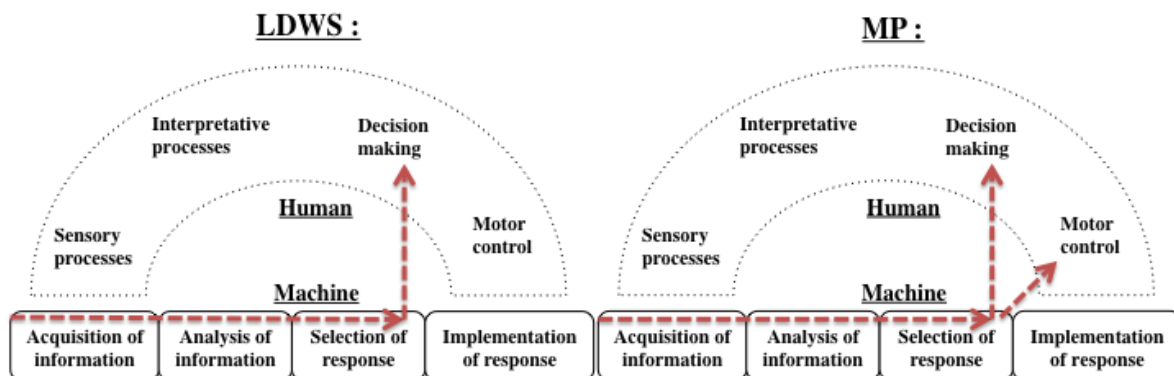
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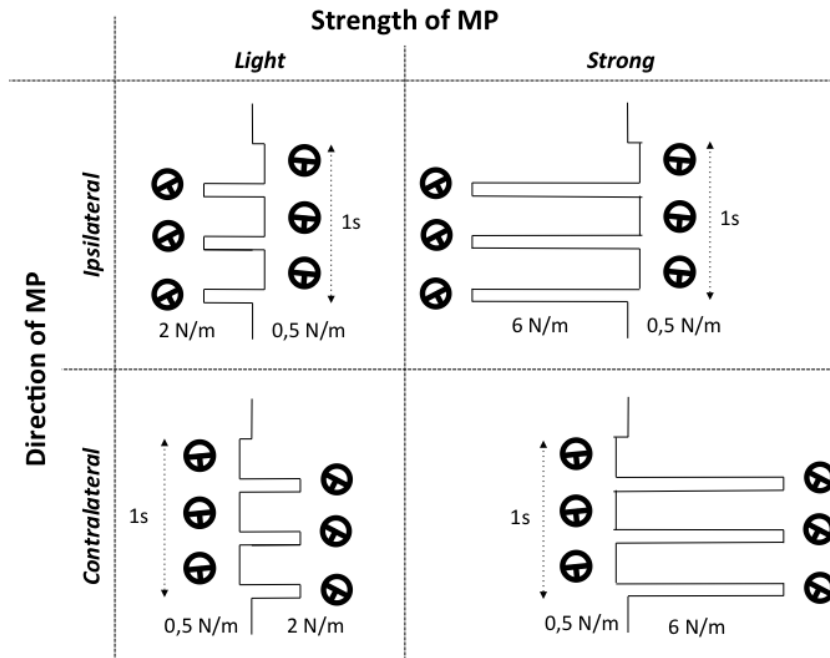
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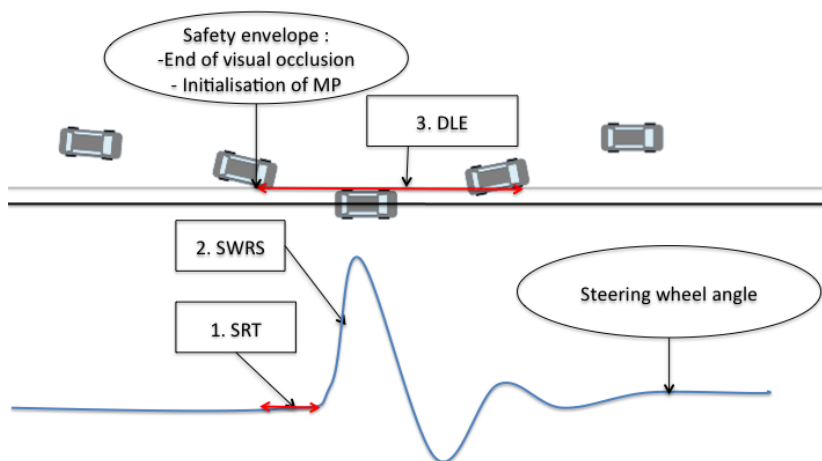
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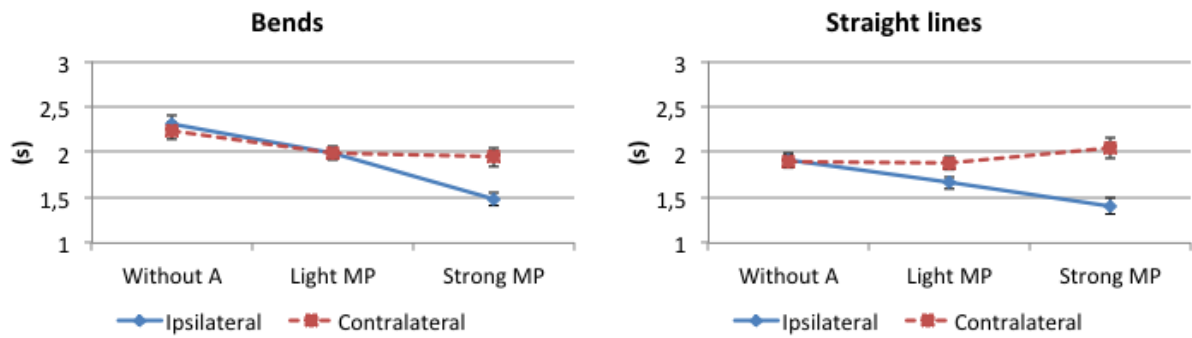
641 **Fig. 1.** Illustration of the different degrees of intervention on a driver's cognitive processes  
 642 with classic LDWS and MP systems.  
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 644  
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646  
 647 **Fig. 2.** Illustration of the four conditions in which MP was active during near lane departure  
 648 on the right. The MP strength was either 2 N/m (light MP) or 6 N/m (strong MP). MP was  
 649 oriented toward the lane centre (ipsilateral MP) or toward the side of lane departure  
 650 (contralateral MP).  
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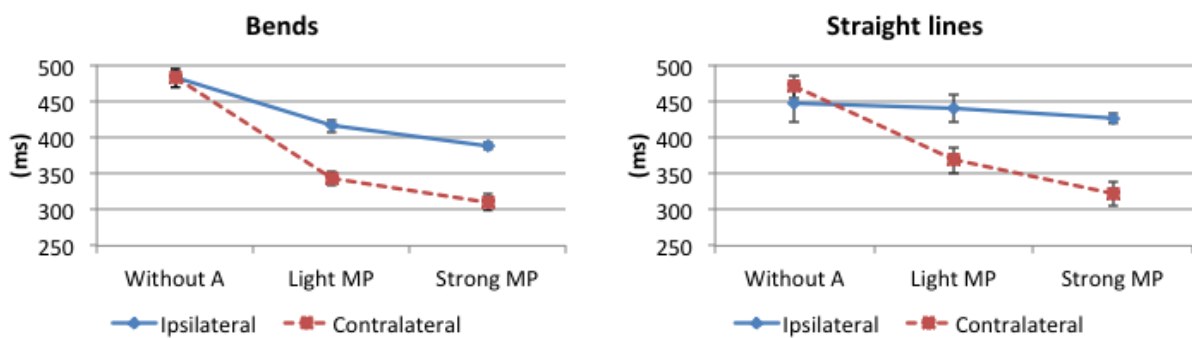


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 656 **Fig. 3.** The three variables; 1. Steering Reaction Time (SRT); 2. Maximum Steering Wheel  
 657 Rotation Speed (SWRS); 3. Duration of Lateral Excursion (DLE).  
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 659  
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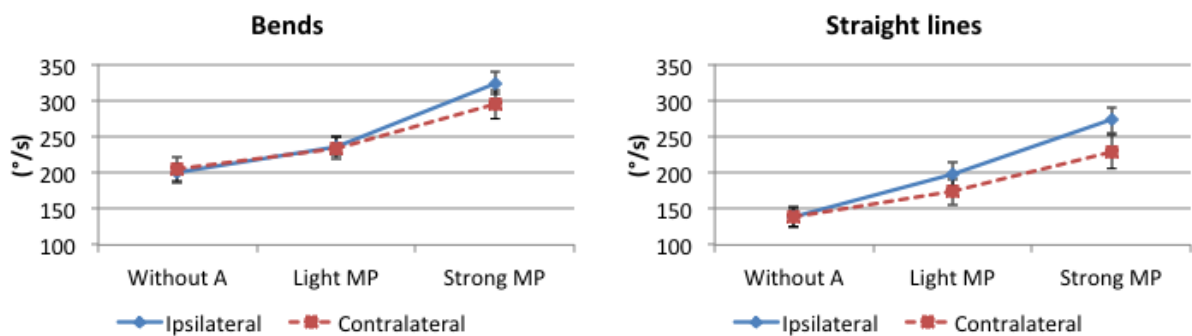
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662 **Fig. 4.** Duration of lateral excursion in bends and in straight lines. Error bars represent  
663 standard errors of the means.  
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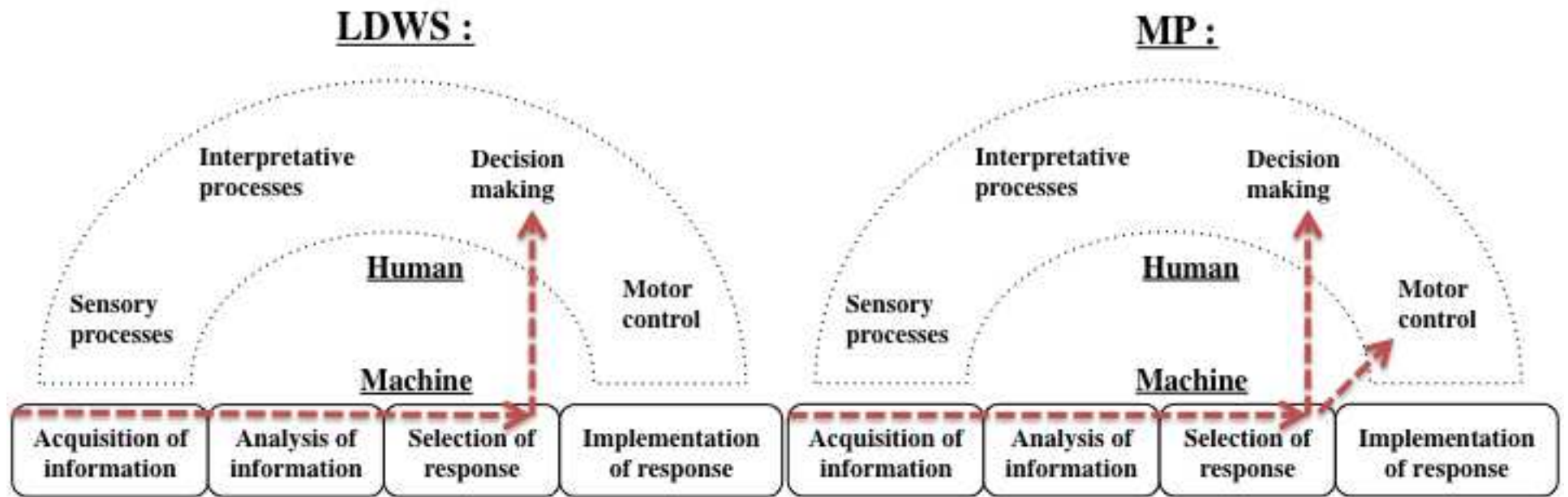


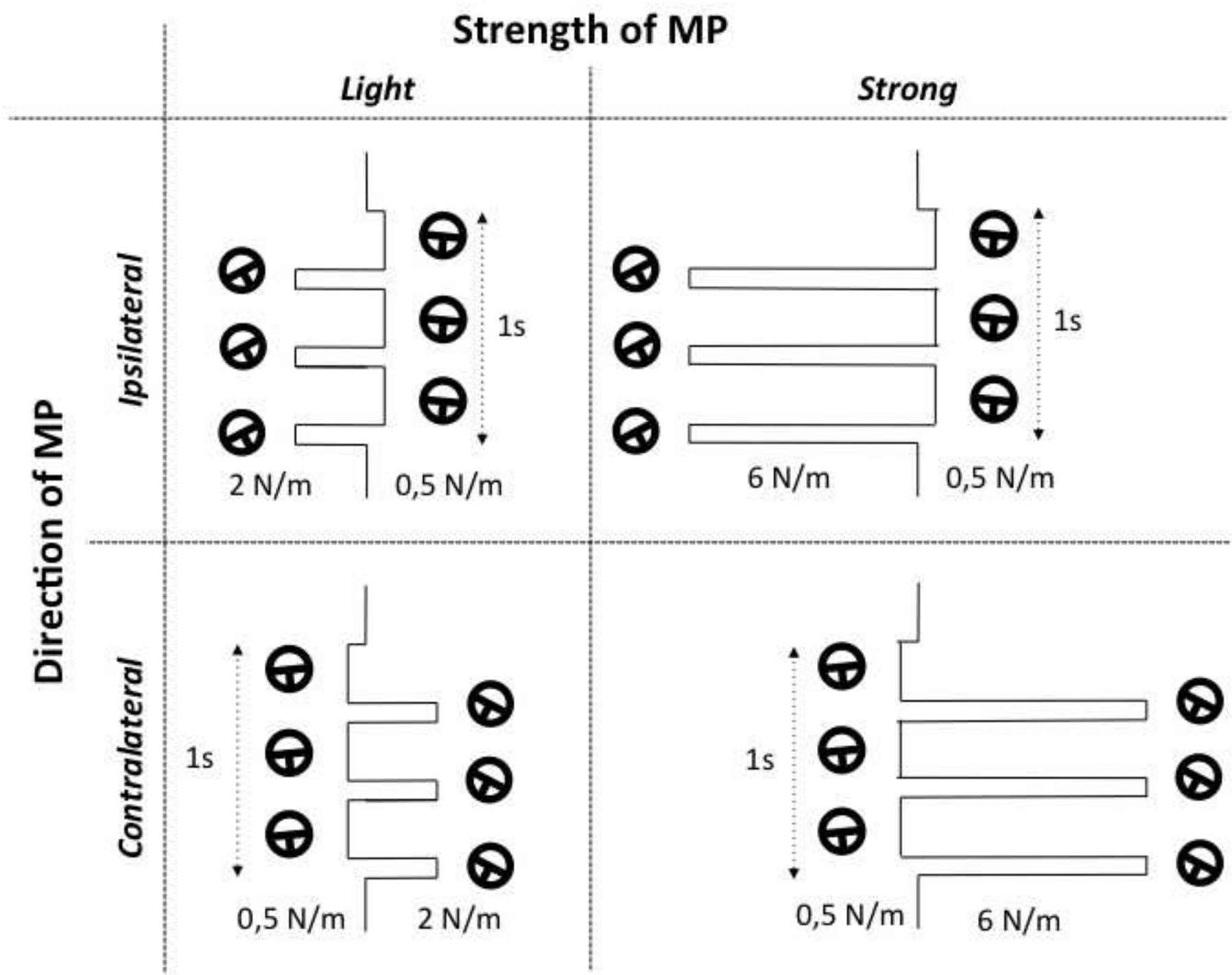
667  
668 **Fig. 5.** Steering reaction times in bends and in straight lines. Error bars represent standard  
669 errors of the means.  
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671  
672



673  
674 **Fig. 6.** Maximum steering wheel rotation speed in bends and in straight lines. Error bars  
675 represent standard errors of the means.  
676





Figure(s)  
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