



HAL
open science

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

Mathieu Deroo, Jean-Michel Hoc, Franck Mars

► **To cite this version:**

Mathieu Deroo, Jean-Michel Hoc, Franck Mars. Effect of strength and direction of haptic cueing on steering control during near lane departure. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2013, 16 (1), pp.92-103. 10.1016/j.trf.2012.08.015 . hal-00743040

HAL Id: hal-00743040

<https://hal.science/hal-00743040v1>

Submitted on 26 Feb 2013

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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 system¹ 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

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.

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 SCANNeR² software package was used with the CALLAS[®] 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.
231

² <http://www.scanersimulation.com/>

232 < INSERT FIGURE 2 HERE >
233

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 ± 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.

287
 288

289 < INSERT FIGURE 3 HERE >

290

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 (δ) 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 δ 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)

314

315 < INSERT FIGURE 4 HERE >

316

317 **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	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*
DLE on straight lines	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*

318
319
320
321
322

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.

323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339

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.

340
341
342
343
344

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
SRT on bends	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*

SRT on straight lines	S,D	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	$ \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	p=0.0001*
	D for s2	d=104.2	$\delta > 80.4$	t(12)=5.95	p=0.0001*

345
346
347
348
349

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.

350
351
352

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).

353
354
355
356
357

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).

358
359
360
361
362

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).

363
364
365

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
SWRS on bends	S,D	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	<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	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	<i>no gen.</i>	t(12)=1.21	p=0.2479	
SWRS on straight lines	S,D	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*	

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.

538 **Acknowledgements**

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

540 **References**

- 541 Anderson, J.R., Bothell, D., Byrne, M.D., Douglass, S., Lebiere, C. & Quin, Y.L. (2004). An
542 integrated theory of the mind. *Psychological Review*, *111*, 1036-1060.
- 543 Azzi, S., Reymond, G., Mérienne, F. & Kemeny, A. (2011). Eco-driving performance
544 assessment with in-car visual and haptic feedback assistance. *Journal of Computing
545 and Information Science in Engineering*, *11*, 041005.
- 546 Beruscha, F., Wang, L., Augsburg, K. & Wandke, H. (2010). Do drivers steer toward or away
547 from lateral directional vibrations at the steering wheel ? Josef Krems, Tibor Petzoldt,
548 Matthias Henning (Eds.) *Proceedings of European Conference on Human Centred
549 Design for Intelligent Transport Systems HUMANIST publications* – Lyon, 2010.
- 550 Beruscha, F., Augsburg, K. & Manstetten, D. (2011). Haptic warning signals at the steering
551 wheel: A literature survey regarding lane departure warning systems, *Haptics The
552 Electronic Journal of Haptics Research*, *4*, 16-18.
- 553 Boy, F. & Sumner, P. (2010). Tight coupling between positive and reversed priming in the
554 masked prime paradigm. *Journal of Experimental Psychology: Human Perception and
555 Performance*, *36*, 892–905.
- 556 Brookhuis, K., A., de Waard, D. & Fairclough, S., H. (2003). Criteria for driver impairment,
557 *Ergonomics*, *46*, 433-445.

558 Cooke, J.D. (1980). The organization of simple, skilled movements, In: G.E Stelmach, J.
559 Requin (eds.), *Tutorials in motor behaviour* (pp. 199-212). North-Holland Publishing
560 Company, Amsterdam.

561 de Rosario, H., Louredo, M., Díaz, I., Soler, A., Juan Gil, J., Solaz J.S. & Jornet, J. (2010).
562 Efficacy and feeling of a vibrotactile frontal collision warning implemented in a haptic
563 pedal. *Transportation Research Part F: Psychology and Behaviour*, 13, 80-91.

564 Deroo, M., Hoc, J.M. & Mars, F. (2012). Influence of risk expectation on haptically cued
565 corrective manoeuvres during lane departure. *Ergonomics*, 55, 465-475.

566 Eimer, M. & Schlaghecken, F. (2003). Response facilitation and inhibition in subliminal
567 priming. *Biological Psychology*, 64, 7-26.

568 Griffiths, P.G. & Gillespie, R.B. (2005). Sharing control between humans and automation
569 using haptic interface: primary and secondary task performance benefits. *Human*
570 *Factors* 47, 574-590.

571 Guiard, Y. (1983). The lateral coding of rotations: A study of the Simon effect with wheel-
572 rotation responses. *Journal of Motor Behavior*, 15, 331-342.

573 Ho, C., Tan, H., Z. & Spence, C. (2006). Assessing the effectiveness of “intuitive”
574 vibrotactile warning signals in preventing front to rear-end collisions in a driving
575 simulator. *Accident Analysis & Prevention*, 38, 988-996.

576 Hoc, J.M., Young, M.S. & Blosseville, J. M. (2009). Cooperation between drivers and
577 automation: implications for safety. *Theoretical Issues in Ergonomics Science*, 10, 135-
578 160.

579 Hoc, J.M. & Amalberti, R. (2007). Cognitive Control Dynamics for Reaching a Satisficing
580 Performance in Complex Dynamic Situations. *Journal of Cognitive Engineering and*
581 *Decision Making*, 1, 22-55.

582 Kuge, N., Boer, E.R., Yamamura, T., Ward, N.J. & Manser, M.P. (2006). Study on driver’s
583 car following abilities based on an active haptic support function. *SAE Technical Paper*
584 2006-01-0344, doi:10.4271/2006-01-0344.

585 Kullack, A., Ehrenpfordt, I., Lemmer, K., & Eggert, F. (2008). ReflektAS: lane departure
586 prevention system based on behavioural control. *IET Intelligent Transport Systems*, 2,
587 285-293.

588 Kullack, A., Ehrenpfordt, I., & Eggert, F. (2010). REFLEKTAS -- Further Tests of a Fast and
589 Reliable Lane Departure Prevention System for Critical Situations. In: *Proceedings of*
590 *the 16th ITS World Congress and Exhibition on Intelligent Transport Systems and*
591 *Services*. Stockholm, Sweden, 6pp.

592 Lechner D., Delanne Y., Schaefer G., & Schmitt V. (1997). Méthodologie de validation du
593 logiciel de dynamique automobile CALLAS. SIA 970202. *Congrès SIA Lyon*, Avril
594 1997. Reprinted in *Ingénieurs de l’automobile* N°713, May 1997.

595 Lecoutre, B. & Poitevineau, J. (2005). Le logiciel “LePAC”. *La Revue de Modulad*, 33
596 (whole volume). Available from: [http://www.univ-](http://www.univ-rouen.fr/LMRS/Persopage/Lecoutre/PubBL.html)
597 [rouen.fr/LMRS/Persopage/Lecoutre/PubBL.html](http://www.univ-rouen.fr/LMRS/Persopage/Lecoutre/PubBL.html) [Accessed 3 January 2012] (English
598 version)

599 Najm, W. G., Smith, J. D. & Yanagisawa, M., 2007. Pre-crash scenario typology for crash
600 avoidance research. (Tech. Rep. DOT-HS-810 767). Washington, DC: National
601 Highway Transportation Safety Administration Research.

602 Navarro, J., Mars, F. & Hoc, J. M. (2007). Lateral control assistance for car drivers: a
603 comparison of motor priming and warning systems. *Human Factors*, 49, 950-960.

604 Navarro, J., Mars, F., Forzy, J., El-Jaafari, M. & Hoc, J. (2010). Objective and subjective
605 evaluation of motor priming and warning systems applied to lateral control assistance.
606 *Accident Analysis & Prevention*, 42, 904-912.

607 Navarro, J., Mars, F., & Young, M.S. (2011). Lateral control assistance in car driving:
608 classification, review and future prospects. *IET Intelligent Transport Systems*, 5, 207-
609 220.

610 Onimaru, S. & Kitazaki, M. (2010), Visual and tactile information to improve drivers
611 performance. In: *Proceedings of the IEEE Virtual Reality Conference (VR)* (pp. 295-
612 296), Waltham, Massachusetts.

613 Parasuraman, R., Sheridan, T. & Wickens, C. (2000). A model for types and levels of human
614 interaction with automation. *IEEE Transactions on Systems, Man and Cybernetics, Part*
615 *A: Systems and Humans*, 30, 286-297.

616 Prochazka, A., Clarac, F., Loeb, G.E., Rothwell, J.C. & Wolpaw, J.R. (2000). What do reflex
617 and voluntary mean ? Modern views on an ancient debate. *Experimental Brain*
618 *Research*, 130, 417-432.

619 Rasmussen, J. (1986). *Information processing and human-machine interaction*. Elsevier,
620 Amsterdam.

621 Rouanet, H. (1996). Bayesian methods for assessing importance of effects. *Psychological*
622 *Bulletin*, 119, 149-158.

623 Rouanet, H. & Lecoutre, B. (1983). Specific inference in ANOVA: from significance tests to
624 Bayesian procedures. *British Journal of Mathematical and Statistical Psychology*, 36,
625 252-268.

626 Sumner, P. (2007). Negative and positive masked-priming-Implications for motor inhibition.
627 *Advances in Cognitive Psychology*, 3, 317-326.

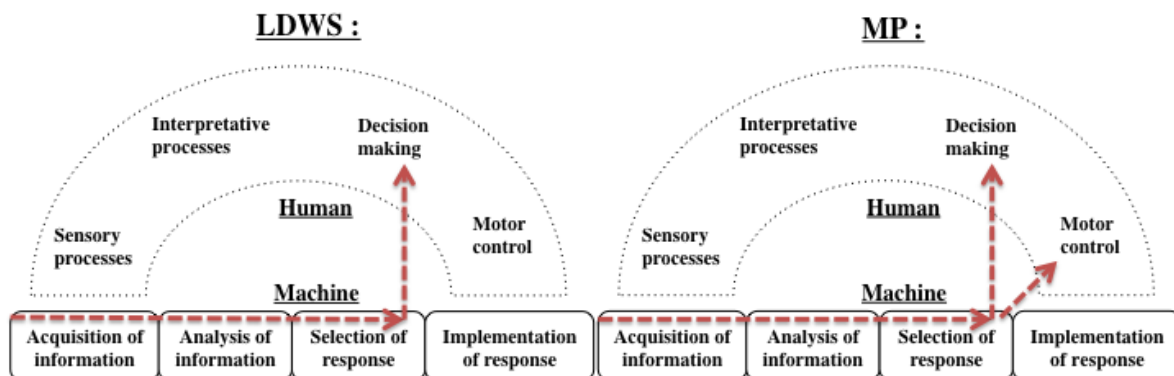
628 Suzuki, K. & Jansson, H. (2003). An analysis of driver's steering behaviour during auditory
629 or haptic warnings for the designing of lane departure warning system. *Japan Society of*
630 *Automotive Engineers Review*, 24, 65-70.

631 Stanley, L.M. (2006). *Haptic and auditory interfaces as collision avoidance technique during*
632 *roadway departures and driver perception of these modalities*. Doctoral dissertation,
633 Montana State University, Montana.

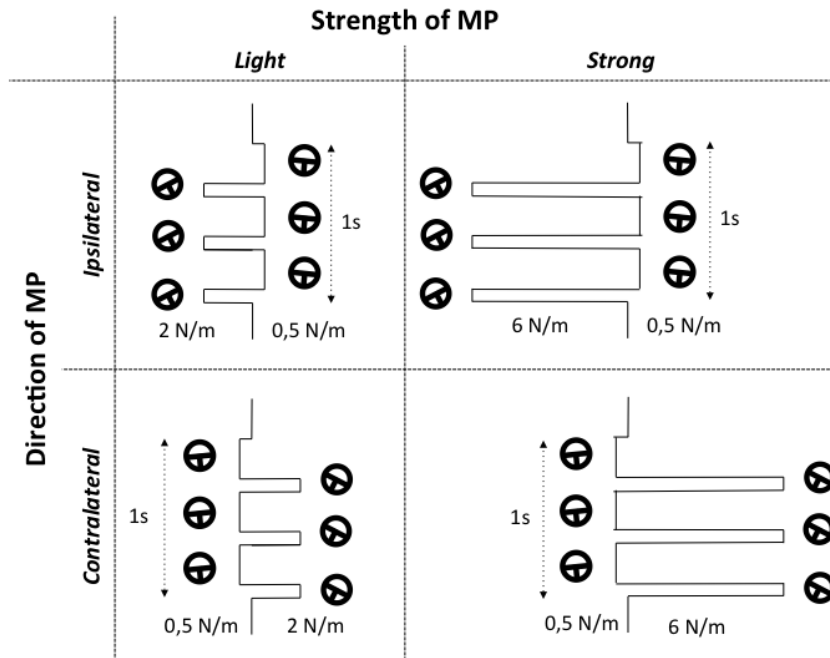
634 UNECE (2007). *Statistics of Road Traffic Accidents in Europe and North America*, 51st ed.
635 UNECE, Geneva, 46-61.

636 Wilson, A.D., Tresilian, J.R. & Schlaghecken, F. (2010). Continuous priming effects on
637 discrete response choices. *Brain and Cognition*, 74, 152-159.

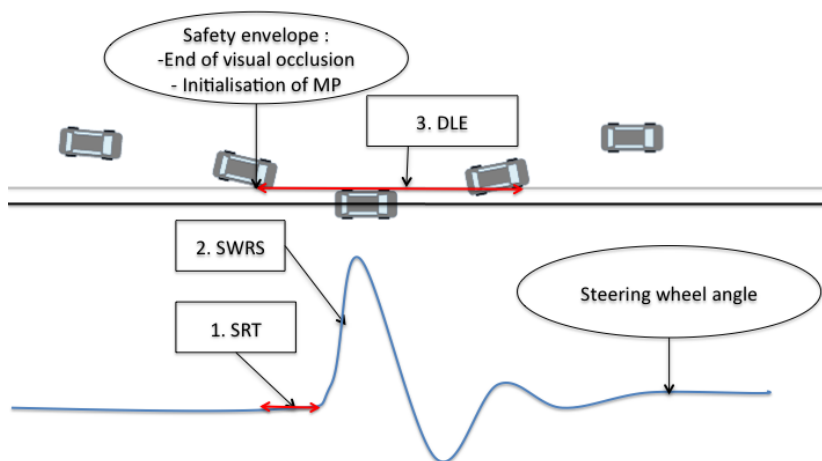
638
639



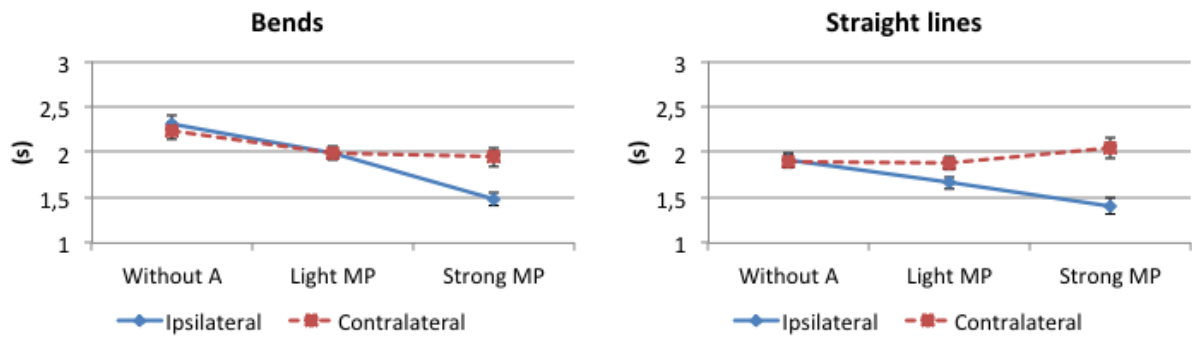
641 **Fig. 1.** Illustration of the different degrees of intervention on a driver's cognitive processes
 642 with classic LDWS and MP systems.
 643
 644
 645



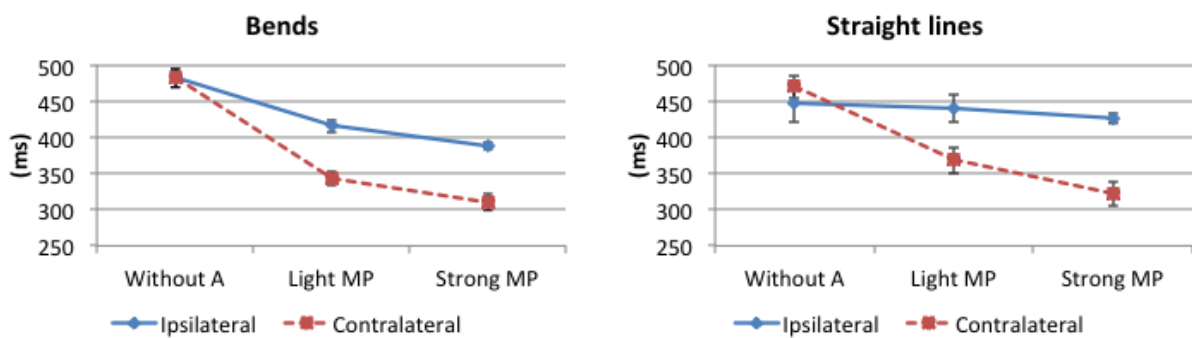
646
 647 **Fig. 2.** Illustration of the four conditions in which MP was active during near lane departure
 648 on the right. The MP strength was either 2 N/m (light MP) or 6 N/m (strong MP). MP was
 649 oriented toward the lane centre (ipsilateral MP) or toward the side of lane departure
 650 (contralateral MP).
 651
 652
 653
 654



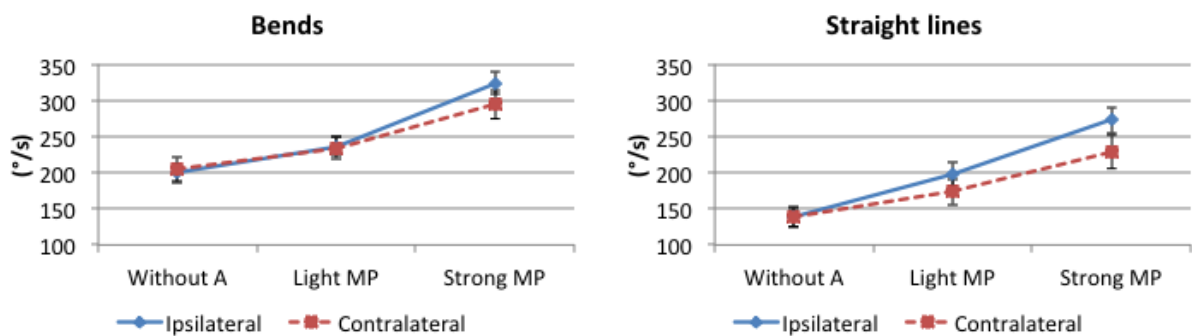
655
 656 **Fig. 3.** The three variables; 1. Steering Reaction Time (SRT); 2. Maximum Steering Wheel
 657 Rotation Speed (SWRS); 3. Duration of Lateral Excursion (DLE).
 658
 659
 660



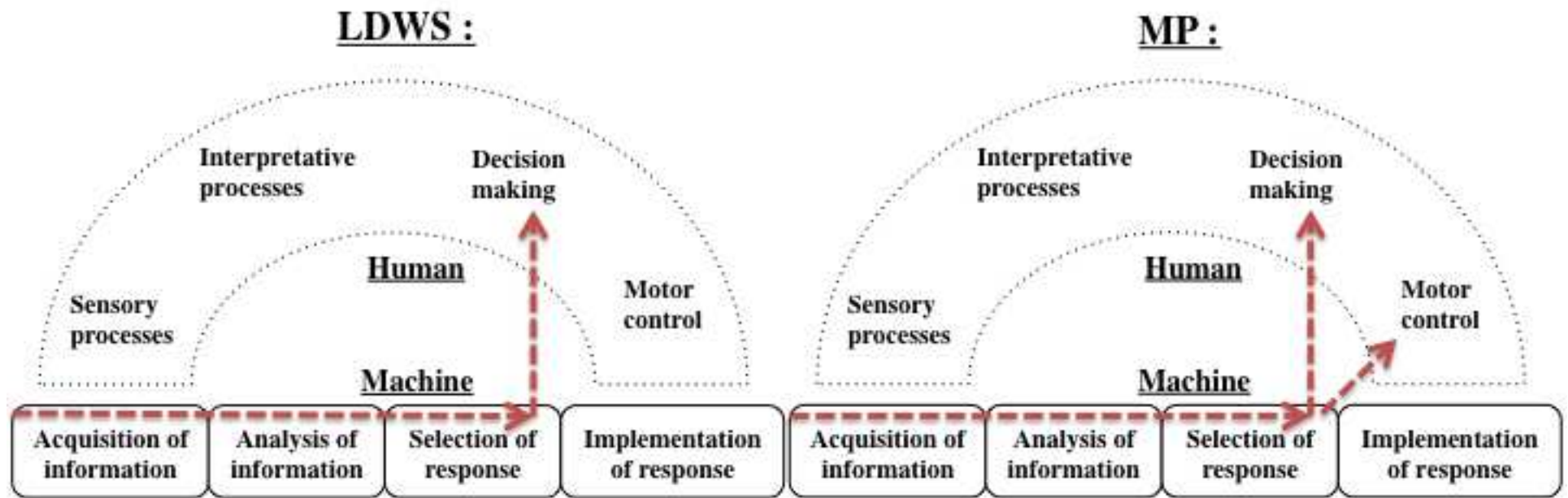
661
662 **Fig. 4.** Duration of lateral excursion in bends and in straight lines. Error bars represent
663 standard errors of the means.
664
665
666

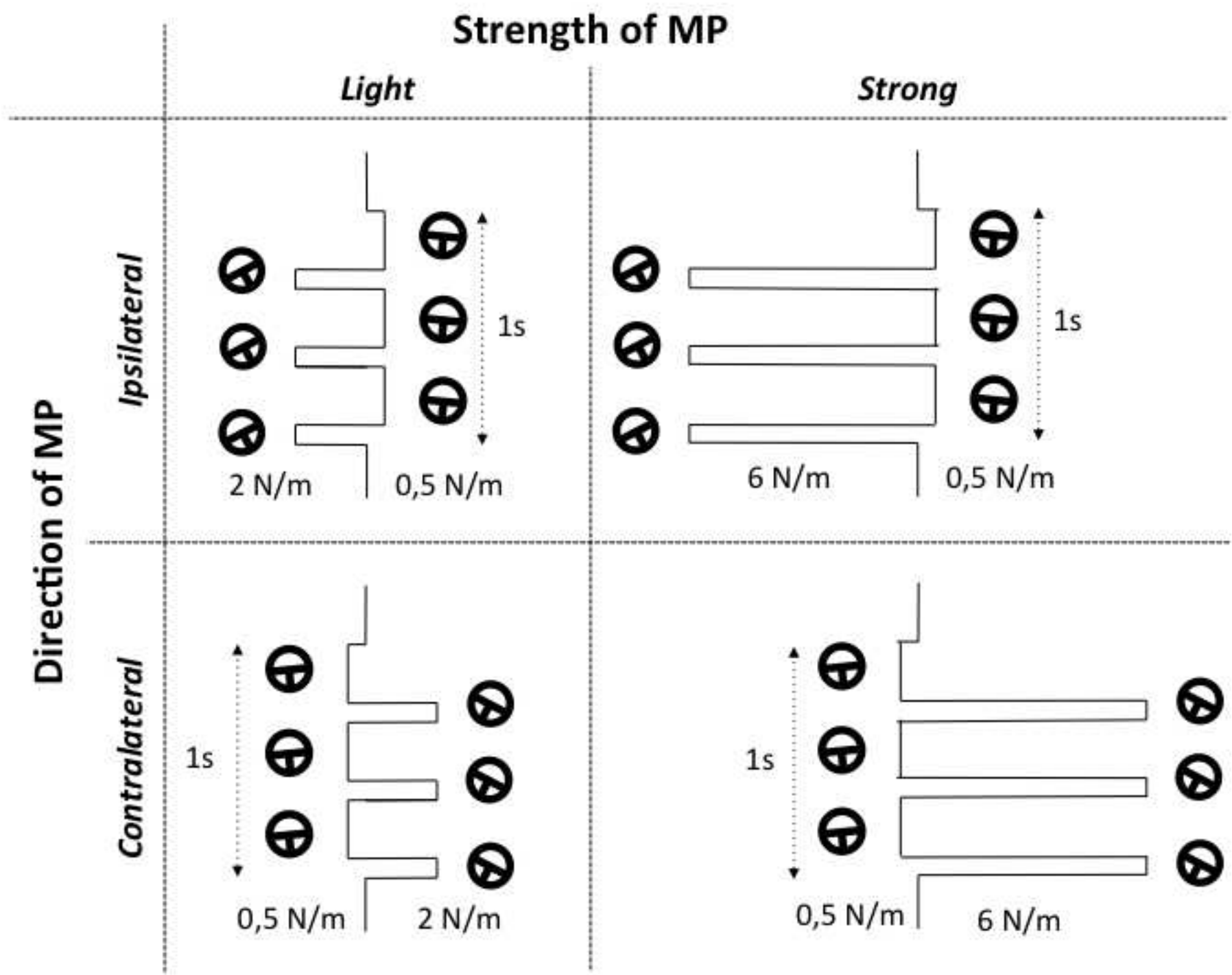


667
668 **Fig. 5.** Steering reaction times in bends and in straight lines. Error bars represent standard
669 errors of means.
670
671
672



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





Figure(s)
[Click here to download high resolution image](#)

