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Objective and subjective evaluation of motor priming and warning systems applied to lateral control assistance

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ABSTRACT

Previous research has shown that a device called "motor priming" (MP) was more effective than other lane departure warning systems. MP prompts drivers to take action by means of small asymmetric oscillations of the steering wheel. The first objective of this experiment was to provide a deeper understanding of MP mechanisms through a series of comparisons with other haptic and auditory systems. The results suggest that much of the improvement in recovery manoeuvres observed with MP is due to the motor cue (proprioceptive pre-activation of the gesture). Other factors, such as delivering the signal directly to the hands (stimulation of response effectors) or using the tactile modality rather than auditory warning, play a lesser role. This supports the hypothesis that MP devices directly intervene at the motor level, in contrast to more traditional warning systems, which only improve situation diagnosis. The second objective was to assess drivers' acceptance of the assistance devices. A dissociation between efficiency and acceptance of the devices was observed: drivers globally preferred auditory warning to MP. The combination of auditory warning and motor priming appeared to be a good compromise to achieve both effectiveness and acceptance. This experiment illustrates the relevance of simulator studies when dangerous situations are the main targets of the investigation.

1. Introduction

Najm et al. (2007) have estimated that accidents that follow an unintended lane departure represent more than 27% of all single vehicle crashes. For this reason, helping drivers to keep their vehicle on the road has become a challenge for car manufacturers. A consequence of this situation is the development of ESP (electronic stability program), which targets loss of control crashes by acting on the vehicle dynamics when skidding has already started. Although such a last-second intervention can be beneficial in some cases, efforts have also been made to improve the driver's behaviour before the car enters in such a critical situation. The evaluation of devices designed to intervene in dangerous situations is a classic example of simulator use, where scenario and traffic context controllability is very high. It allows placing participants in critical or near-to-critical situations without putting them at harmful risks.

Hoc et al. (2009) put forward a four-level classification system in order to categorize driving assistance devices within the framework of human–machine cooperation (Hoc, 2001). First, perceptive mode devices provide uninterpreted information in order to enhance the drivers' perception (e.g. speedometer). The mutual control mode includes devices that either provide a criticism on driver behaviour (e.g. collision warning) or act on the vehicle commands without actually taking control (e.g. resistance in the accelerator pedal). Function delegation mode devices are in use when the drivers decide to delegate part of the driving functions for a while (e.g. cruise control). Finally, in fully automatic mode, the driver would become the supervisor of automation which carries out the whole driving task. Fig. 1 summarizes this classification with its application to lateral control.

All the devices assessed in this study belong to the "mutual control" category. For lateral control, they can be split into two subcategories: lane departure warning systems (LDWS) and lane keeping assistance systems (LKAS). LKAS actively intervene on the steering wheel. For instance, torque may be continuously applied to the steering wheel in order to help drivers remain close to the lane centre. This is truly shared control, where the actions of the automation device should blend into the driver's sensorimotor control loop (Griffiths and Gillespie, 2005). Contrary to LKAS, LDWS do not directly influence steering at the action level. They warn that the lateral position in the lane is unsafe, thus improving the situation diagnosis made by the driver.

Navarro et al. (2007) proposed a new type of assistance device called "motor priming". The rationale for this device was to take the best of both LDWS and LKAS categories: to act at the action

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level, with anticipated gains in effectiveness, but with minimal direct action on steering control. Intervention at a motor level, without intruding into vehicle control, is performed through asymmetric oscillations of the steering wheel when the car is about to cross one of the lane edge lines. More precisely, the device delivers small alternating movements to the steering wheel (Fig. 3). The first movement is directed toward the road centre. This movement and subsequent movements in the same direction are characterized by a torque applied to the steering wheel that is stronger than the movements in the opposite direction (the side of lane departure). It gives the sensation of gentle pushes on the steering wheel in the direction of the expected response. The aim is to pre-activate the corrective gesture at the proprioceptive level, without actually performing it on the driver's behalf. The motor priming (MP) device was compared to more traditional warning devices, such as a simple steering wheel vibration or a sound indicating the side of lane departure. The benefits of all assistance devices were measured during lane departures that were generated by occluding the driving scene at specific locations. Results showed that all driving assistance devices improved recovery manoeuvres in comparison to a condition without assistance. The drivers spent less time in a dangerous lateral position. The benefits were significantly larger when MP was delivered, either alone or in combination with auditory warning. The results reported by Navarro et al. (2007) support the idea that MP not only improves situation diagnosis, in the same way as LDWS, but also provides a motor cue to the effectors of the corrective manoeuvre, i.e. the hands.

Within this context, the first objective of the current experiment was to further investigate the determinants of benefits associated with the MP approach. For this, a progressive method was used which compared assistance devices that were increasingly different from MP. The aim was to assess the relative contribution made by the different characteristics which define the MP mode to the observed benefits on recovery manoeuvres. The first step was to compare the MP to a lateralized vibratory warning on the steering wheel. Both devices were identical (i.e. they both provided directional information to the hands by means of the haptic modality), with the exception of the motor prompt which characterizes motor priming. This comparison will isolate the specific role of the motor cue in the improvement of recovery manoeuvre. Improved responses from the driver may also be achieved because the warning signal is delivered directly to the hands, which are the effectors of the manoeuvre. To determine the proper effect of the localization of the stimulus, a comparison was made between the lateralized vibratory warning on the steering wheel and a lateralized vibratory warning on the seat. Both devices gave directional information via the haptic modality, but at different locations. Finally, the use of the haptic modality rather than a more traditional auditory signal may explain some of the benefits associated with motor priming (Sklar and Starter, 1999; van Erp and van Veen, 2004). In an attempt to isolate this factor, the lateralized vibratory warning on the seat was compared to a lateralized warning sound.

Beyond effectiveness, the assistance devices need to be designed in such a way that drivers actually wish to use them. Indeed, well-accepted devices have the tendency to be used more often. For example, Young and Regan (2007) found that drivers used cruise control devices more frequently when they had a more positive attitude towards them. Even if an assistance device can objectively be proven to be effective, the driver may choose to switch it off if, for instance, it is judged too intrusive. Therefore acceptance is a key element in the global assessment of MP. An example of this is given by Young and Regan (2007), who noted that cruise control and speed alerting devices, supposed to help avoid excessive speeding, are typically set up to 15 km above the speed limit. At the same time, participants had a positive attitude towards the systems and felt that these devices were generally effective in helping them to control their speed. Similarly, Ho et al. (2006) found that drivers preferred distinctive alarms for different warning systems, even though the results showed that objective performance was the same whether a single master alarm or multiple alarms were used. Therefore two devices with the same level of effectiveness could result in very different levels of acceptance. Ideally, the design of assistance devices should be directed by an objective to optimize both effectiveness and acceptance.

The secondary objective of the experiment was to assess drivers' acceptance of all driving assistance devices in parallel with their objective effects on steering behaviour. According to Nielsen (1993, p. 24), system acceptability can broadly be defined as "the question of whether the system is good enough to satisfy all the needs and requirements of the users". In this study, the subjective satisfaction dimension, defined as "how pleasant it is to use the system", has been more specifically targeted. Various methods are traditionally used to evaluate acceptance. The main evaluation techniques are focus groups (interviews on small groups to perform qualitative evaluation of the object), simulated or field trials with acceptability questionnaires (e.g. van der Laan et al., 1997), attitudinal surveys and stated preference techniques (Comte et al., 2000). In the current experiment, drivers were asked to rank the different devices in terms of preference. Focus group non-directive interviews were conducted as a complement to the stated preference technique in order to gain insight into the cognitive, affective and sensorial dimensions of drivers' acceptance (Cahour, 2008). Of particular interest was the subjective assessment of MP, since this intervenes at the action level. Some studies on cruise control have revealed that, if drivers were not feeling in control of the car, they tended to stop using the device (Young and Regan, 2007) or perceive the device as less acceptable (Comte et al., 2000). In addition, drivers' judgements may not favour an automation device which acts on the steering wheel, even if it does not interfere with their control of the vehicle (Lefeuvre et al., 2004). It is hypothesized that, because of its action on the steering wheel (i.e. the car's main mean of control) and the motor prompt it provides, MP would be less acceptable than other devices. Conversely, an auditory warning device that mimics the familiar sound of rumble strips can be expected to be

Human-machine cooperation mode	Perception mode	Mutual control mode		Delegation function mode	Fully automatic mode
Example for lateral control assistance device	Road edges enhancement	Lane departure warning systems (LDWS)	Lane keeping assistance systems (LKAS)	Automatic steering	Automatic pilot

Fig. 1. Classification of human–machine cooperation modes proposed by Hoc et al. (2009). Bottom row: examples of lateral control devices for each mode.

more acceptable. Indeed, situation diagnosis is known to be based on the matching of the perception of an event and the previous knowledge of similar events (Wickens and Hollands, 2000). Giving easily identified signals to the driver may be the best way to make driving assistance more acceptable. Thus, a combination of motor priming and auditory warning was also studied. Navarro et al. (2007) demonstrated that such a combination yielded an effect on recovery manoeuvres that was similar to the unimodal MP mode. However, a difference may exist in terms of acceptance. It may be a case of finding an optimal compromise between effectiveness (brought about by motor priming) and acceptance (brought about by auditory warning).

In summary, this study is a follow-up to Navarro et al. (2007) for the validation of the MP principle. Through a more complete series of comparisons, the main objective was to determine whether the effectiveness of the device is due to its action at the motor level, its intervention on the steering wheel or the use of the haptic modality. In Navarro et al. (2007), lane departure episodes were provoked by means of controlled visual occlusions. In the present study, a more ecological method was used, in the form of a distraction task requiring visual shifts away from the driving task. In parallel, another objective was to provide some first insights into the acceptability of MP compared to other LDWS.

2. Method

2.1. Participants

Twenty volunteers (4 women and 16 men), between 23 and 52 years of age (mean = 34) took part in this experiment. They were carefully selected among a large database of volunteers working for Renault. The participants were employed in administrative and technical departments other than human factors or any related field. All of them had normal or corrected-to-normal vision. Participants drove between 3000 and 40,000 km per year (mean = 19,800). Fifteen participants declared that they already used an assistance device for personal purposes, mostly electronic stability program, anti-lock braking system or cruise control devices.

2.2. Simulator

The experiment was carried out on a high-fidelity moving-base simulator (Cards2, developed by Renault's Technical Simulation Centre). The simulator uses a generic cockpit with fully operational commands (steering wheel, pedals, gearbox lever, etc.) and an animated dashboard. Force feedback systems are coupled to the steering wheel, the gearbox lever, clutch and brakes, to simulate proper physical response. The 6-axes motion platform uses electromechanical actuators producing accelerations up to 0.5 g within a motion envelope of about 40 cm linear and 20° angular displacement. The visual scene was projected onto three screens with 150° of visual angle. The simulation was generated using the simulation software SCANeR©II (Oktal).

2.3. Route

The visual database represented a two-lane secondary road 3.9 km in length forming a lap (Fig. 2). The lane width was approximately 3.50 m. Road signs (including speed limits and bend warnings) were positioned along the road. The driving speed was limited to 80 km/h in straight lanes and 70 km/h in bends. Sharp bends and intersections were limited to 50 km/h. Oncoming traffic was present at a rate of approximately four vehicles per kilometre and at a speed of 50 km/h. However, the traffic was arranged in such a way that the drivers never had to take into account a potential risk of collision.

2.4. Driving assistance devices

Five test conditions which used a specific device were compared to a control condition (without assistance: WA). All assistance devices were brought into action each time the centre of the vehicle moved more than 85 cm from the lane centre. They remained active as long as the vehicle position exceeded this threshold.

- Auditory warning (AW): a sound was broadcasted through the loudspeaker placed in the door of the simulator on the side of lane departure. The sound simulated a rumble strip noise, known to be an effective infrastructure-based warning signal (Rosey et al., 2008).
- Wheel vibratory warning (WVW): two vibrators were inserted in the upper part of the steering wheel, one on each side. Foam separation between the right and left half of the steering wheel prevented the vibration on one side from being felt on the other side. The active vibrator indicated the direction of lane departure.

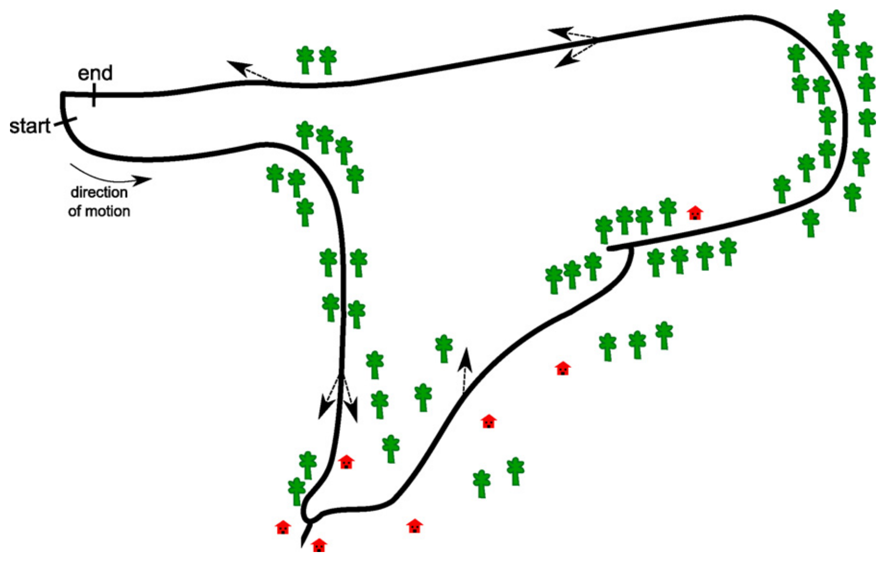

Fig. 2. Layout of the track. The dotted arrows indicate the start of the critical situations (start of the distraction task) and the potential direction of lane departures.

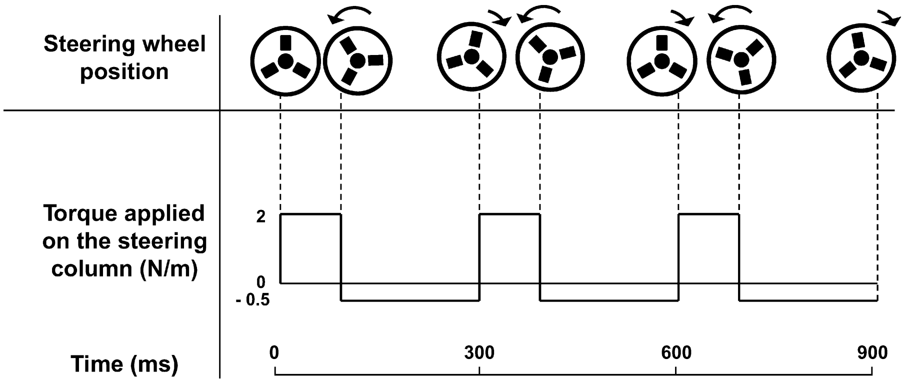

Fig. 3. Schematic representation of MP in action. The example corresponds to a lane departure to the right. The amplitudes of steering wheel rotations were exaggerated for the sake of illustration. When the driver holds the steering wheel, most of the actual motion is dampened.

- Seat vibratory warning (SVW): a set of vibrators was placed in the right and left sides of the base and back of the seat. The active vibrators indicated the direction of lane departure.
- Motor priming (MP): an asymmetric steering wheel oscillation was generated, with torque being stronger (2 N/m, 100 ms) in the direction of the lane centre and weaker (0.5 N/m, 200 ms) in the direction of lane departure. The period of the oscillation was 300 ms (Fig. 3).
- Auditory and motor priming (AMP): the AW and the MP devices were combined. The auditory and haptic components were triggered at the same time. However, the frequencies of both signals differed.

2.5. Distraction task

Lane departures were brought about by means of a reading task. This involved participants reading a succession of words displayed on a monitor placed on the dashboard (the position usually occupied by a car radio). While driving, participants were instructed to read aloud as many words as possible without looking at the road for the period of the distraction task. During that task, the vehicle trajectory was slightly changed in order to take the car in one direction or the other. This was done using a lateral perturbation. The perturbation acted on the vehicle dynamics, which yielded a lateral drift of the car in the desired direction, but had no effect on the moving platform or on the steering wheel force feedback. Since drivers were distracted during that time, they were unaware of the change in heading. The distraction task stopped when the vehicle reached the activation threshold of the assistance device (85 cm).

From a general point of view, the number of distraction task by lap varied from two to four. Fig. 2 indicates the four positions of the track (two moderate bends and two straight lines) where lane departure episodes occurred with all driving assistances. The analyses were performed on these data. The side of lane departure was counterbalanced in straight lines. In order to avoid the distraction task becoming too predictable, additional distraction tasks were sometimes started at other position of the track. Of these episodes some did not lead to a lane departure, some did. In all cases, the data was not analysed for these additional distraction tasks because all devices were not assessed at those locations.

2.6. Procedure

Drivers were instructed to drive in the right-hand lane, respect speed limits and keep both hands on the steering wheel in a position close to the “ten-to-two” position. The study lasted about 90 min and consisted of 10 laps, followed by an interview. Each of the five assistance devices was assessed over the course of one lap. Laps with assistance were interleaved with laps without assistance. The order of presentation of the different assistance devices was counterbalanced between drivers. After each lap with assistance, drivers were briefly asked the following question about the device they had just experienced: “Please could you quickly describe what happened when lane departure occurred?”

After the driving test, an open interview inspired by explicitation techniques (Vermersch, 1994) was performed. These techniques allow the exploration of implicit, pre-thought-out aspects of a physical or mental action. The interviewer guided drivers to put their experience into words. This method aimed at collecting verbal reports on feelings, sensations, internal states, and thoughts that were experienced by the driver with each assistance device. Drivers were also asked to rank the assistance devices in order of preference (without ties) from the best (1) to the worst (5).

2.7. Data analysis

To assess drivers' performance, several variables were analysed. The main variable was the time spent by drivers outside the safety envelope of 85 cm from the lane centre, from the moment when lane departure was imminent (lateral position >85 cm) to the moment that the car returned to a normal position in the lane (lateral position <85 cm). This will be referred to as the duration of lateral excursion. Steering reaction times were computed to test drivers' reactivity after lane departure. This variable corresponds to the time between the end of the distraction task and the drivers' first action on the steering wheel. The peak acceleration of steering wheel motion once the recovery manoeuvre was engaged was also calculated. This variable represents the sharpness of the steering reaction. Finally, the corrective overshoot was computed; that is to say the distance between the lane centre and the maximum lateral position in the direction of the lane border opposite to lane departure. Fig. 4 represents the sequence of events during a critical situation and what the dependant variables represent in that sequence.

In order to evaluate the effects of the assistance devices and their differences, the value of the control condition without assistance was subtracted from all test conditions and two-ways analyses of variance, with the type of assistance (5 types) and the type of road section (bends vs. straight lines) as factors, were carried out on these data sets. The effect of the type of road appeared small and the results that will be presented will be related to the effect of the type of assistance on the average. Most of the time, the test statistics was a t test (one degree of freedom) and, sometimes a F test (several degrees of freedom). In each case, the tests of significance was supplemented by a variant of Bayesian statistical inference (fiducial inference: see Lecoutre and Poitevineau, 2005; Rouanet, 1996;

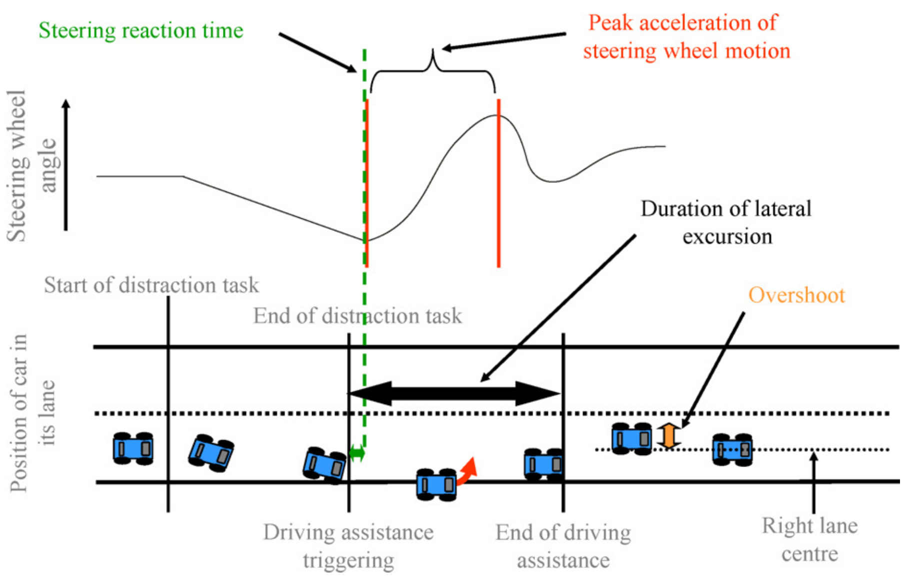

Fig. 4. Schematic representation of a sequence of events and the meaning of dependant variables during critical situations.

Rouanet and Lecoutre, 1983) in order to conclude on the population effect size (δ) on the basis of the observed effect (d), sample size and variability. The method considers the power of the test in order to draw conclusions on the population effect size for which we have chosen the guarantee of .90. In the case of F (several degrees of freedom), d and δ are the quadratic means of the effects.

All analyses of subjective data were carried out on 18 participants because the data for two participants was lost due to a technical problem. The order of preference given by the participants was compared across assistance devices by means of a Friedman test (global effect) and sign tests (paired comparisons). An analysis of content was carried out on post-experimental reports. First, the topics which were spontaneously brought up by drivers were categorized into positive and negative comments. Then, verbal reports related to drivers' acceptance were extracted and classified. The analysis of content underlined four discursive categories: (a) sensation (feeling, pleasantness, intrusiveness, etc.); (b) understanding (identification of how the system works and the corrective action

Table 1
Summary of the statistical analyses performed on the effects of all devices in comparison with the condition without assistance. For each dependent variable and each comparison, the table shows the observed effect (d), the Bayesian conclusion on the size of the population effect (δ) with a guarantee γ of .90, the test statistics of the null hypothesis, and the two-tailed level of significance. In the case of a comparison with more than one degree of freedom, d and δ are taken for the quadratic means of the effects. AW: auditory warning; SVW: seat vibration warning; WVW: wheel vibration warning; MP: motor priming; AMP: auditory and motor priming.

Variable	Comparison	d	Bayesian conclusion	Test	LoS
Duration of lateral excursion in seconds	AW	−0.235	$\delta < -0.122$	$t(15) = -2.792$	$p < .02$
	SVW	−0.204	$\delta < -0.095$	$t(15) = -2.513$	$p < .03$
	WVW	−0.301	$\delta < -0.159$	$t(15) = -2.841$	$p < .02$
	MP	−0.624	$\delta < -0.467$	$t(15) = -5.300$	$p < .0001$
	AMP	−0.540	$\delta < -0.409$	$t(15) = -5.523$	$p < .0001$
	AW–SVW–WVW vs. MP–AMP	0.336	$\delta > 0.272$	$t(15) = 7.703$	$p < .0001$
	AW vs. SVW vs. WVW	0.070	$\|\delta\| < 0.158$	$F(2,30) = 0.820$	$p > .45$
	MP vs. AMP	−0.084	$\|\delta\| < 0.230$	$t(15) = -0.793$	$p > .22$
Peak acceleration of steering wheel motion in degrees/second^2	AW	0.351	$\delta > 0.146$	$t(15) = 2.292$	$p < .04$
	SVW	0.426	$\delta > 0.269$	$t(15) = 3.633$	$p < .003$
	WVW	0.038	$\|\delta\| < 0.156$	$t(15) = 0.470$	$p > .64$
	MP	0.933	$\delta > 0.772$	$t(15) = 7.773$	$p < .0001$
	AMP	1.024	$\delta > 0.880$	$t(15) = 9.536$	$p < .0001$
	WVW vs. AW–SVW	−0,350	$\delta < -0.213$	$t(15) = -3.417$	$p < .004$
	AW–SVW vs. MP–AMP	−0.590	$\delta < -0.426$	$t(15) = -4.826$	$p < .0002$
	AW vs. SVW	−0.075	$\|\delta\| < 0.239$	$t(15) = -0.644$	$p > .27$
	MP vs. AMP	−0.091	$\|\delta\| < 0.258$	$t(15) = -0.745$	$p > .47$
Steering reaction time	AW	−0.021	$\|\delta\| < 0.053$	$t(15) = -0.922$	$p > .37$
	SVW	−0.017	$\|\delta\| < 0.052$	$t(15) = -0.695$	$p > .25$
	WVW	−0.092	$\delta < -0.063$	$t(15) = -4.218$	$p < .0007$
	MP	−0.053	$\|\delta\| < 0.105$	$t(15) = -1.387$	$p > .19$
	AMP	−0.070	$\delta < -0.038$	$t(15) = -2.897$	$p < .02$
	AW–SVW vs. WVW	0.072	$\delta > 0.048$	$t(15) = 4.010$	$p < .002$
	AW–SVW vs. WVW–MP–AMP	0.052	$\delta > 0.026$	$t(15) = 2.637$	$p < .02$
Overshoots	AW	0.108	$\delta > 0.074$	$t(15) = 4.322$	$p < .0006$
	SVW	0.069	$\delta > 0.032$	$t(15) = 2.506$	$p < .03$
	WVW	0.119	$\delta > 0.059$	$t(15) = 2.654$	$p < .02$
	MP	0.127	$\delta > 0.077$	$t(15) = 3.387$	$p < .005$
	AMP	0.123	$\delta > 0.088$	$t(15) = 4.695$	$p < .0003$
	AW–WVW–MP–AMP vs. SVW	0.051	$\delta > 0.020$	$t(15) = 2.239$	$p < .05$

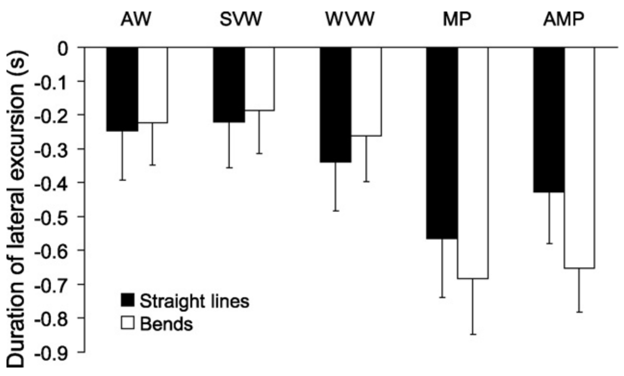

Fig. 5. Effects of all assistance devices on the duration of lateral excursion. The 0 of the *Y* axis corresponds to the baseline obtained in WA (duration = 2.79 and 3.30 s, respectively in straight lines and bends). Error bars represent S.E.M. *N* = 20. AW: auditory warning; SVW: seat vibratory warning; WVW: wheel vibratory warning; MP: motor priming; AMP: auditory and motor priming.

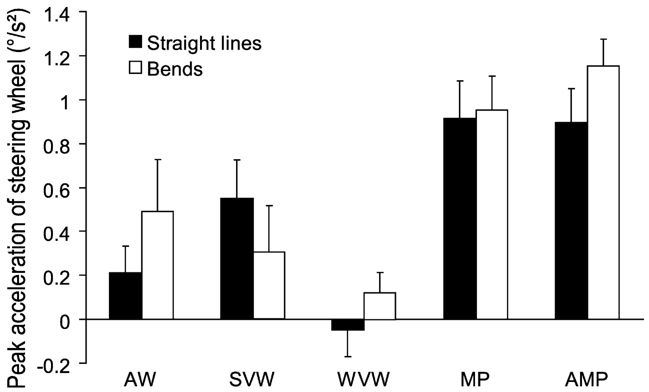

Fig. 6. Effects of all assistance devices on the peak acceleration of steering wheel motion. The 0 of the *Y* axis corresponds to the baseline obtained in WA (peak acceleration = 1.58 and 1.60°/s^2, respectively in straight lines and bends). Error bars represent S.E.M. *N* = 20. AW: auditory warning; SVW: seat vibratory warning; WVW: wheel vibratory warning; MP: motor priming; AMP: auditory and motor priming.

required); (c) perceived utility (would the system be useful in a real car?); (d) attitudes (satisfaction, dissatisfaction, etc.). The number of participants was too low to provide sufficient data for an extensive quantitative analysis to be performed. As a consequence, only recurring comments will be reported here in order to give some qualitative insight into the determinants of the preference rankings.

3. Results

3.1. Steering behaviour

3.1.1. Duration of lateral excursion

The mean duration of lateral excursion without assistance was 2.8 s in straight lines and 3.3 s in bends. Every assistance device notably and significantly reduced the duration by about 0.1–0.5 s at least (Table 1 and Fig. 5). However, the motor priming devices (MP and AMP) reduced the duration notably and significantly more than the warning devices (AW, SVW, and WVW). The absolute values of the differences within the warning devices effects (less than 0.16 s) or within the motor priming devices effects (less than 0.23 s) remained below the differences between the effects of these two types of assistance (at least 0.27 s).

3.1.2. Peak acceleration of steering wheel motion

The peak acceleration of steering wheel motion without assistance was 1.58°/s^2 in straight lines and 1.60°/s^2 in bends, on the average. Every assistance device, except WVW, increased the peak notably and significantly by about 0.15–0.9°/s^2 at least (Table 1 and Fig. 6). The effect of WVW was not significant and its size was less notable (absolute value lower than 0.16°/s^2) than for the other devices, except AW. It increased notably and significantly less the peak (difference between effects of at least 0.2°/s^2) than the other warning devices (AW and SVW). The two remaining warning devices increased notably and significantly less the peak (difference of at least 0.4°/s^2) than the motor priming ones (MP and AMP). The differences within the two groups were not significant and lower than the difference between the groups (respectively less than 0.24 and 0.26°/s^2).

3.1.3. Steering reaction time

The mean steering reaction times without assistance were 0.47 s in straight lines and 0.42 s in bends. For this variable (Table 1 and Fig. 7), the conclusions are not as clear-cut as for the previous variables. The warning device on the steering wheel (WVW) notably and significantly reduced the reaction time (more than 63 ms) and much more than the other warning devices (AW and SVW: significant difference larger than 48 ms). Motor priming alone had no significant effect, but it is not possible to say that it was negligible. However, AMP reduced notably and significantly the reaction time (by at least 38 ms). The devices directly acting on the steering wheel (WVW, MP and AMP) yielded notably and significantly a greater reduction of steering reaction times than the other devices (AW and SVW): difference of at least 26 ms.

3.1.4. Overshoots

The mean sizes of overshoots without assistance were 0.25 m in straight lines and 0.31 m in bends. Every assistance device produced notable and significant overshooting (more than 3–9 cm: Table 1 and Fig. 8). However SVW (warning on the seat) gave rise significantly to notably less overshooting than the other devices (difference larger than 2 cm).

3.2. Subjective assessment

3.2.1. Ranking

Fig. 9 presents the distribution of the ranks of preference assigned to all driving assistance devices, from the most acceptable (AW: mean rank = 2.39) to the least acceptable (MP: mean rank = 3.83). WVW (mean rank = 2.83), AMP (mean rank = 2.94) and SVW (mean rank = 3) gave rise to intermediate results. A Friedman ANOVA did not reveal a significant effect of driving assistance on the ranks ($X^2(4) = 5.39$, ns). Paired comparisons (sign test) reached

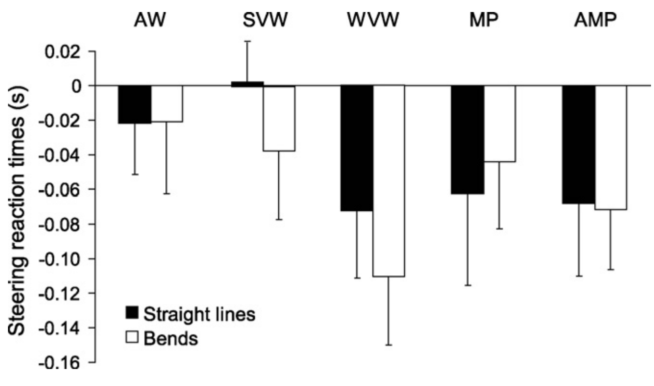

Fig. 7. Effects of all assistance devices on steering reaction time. The 0 of the *Y* axis corresponds to the baseline obtained in WA (reaction time = 0.44 and 0.42 s, respectively in straight lines and bends). Error bars represent S.E.M. *N* = 20. AW: auditory warning; SVW: seat vibratory warning; WVW: wheel vibratory warning; MP: motor priming; AMP: auditory and motor priming.

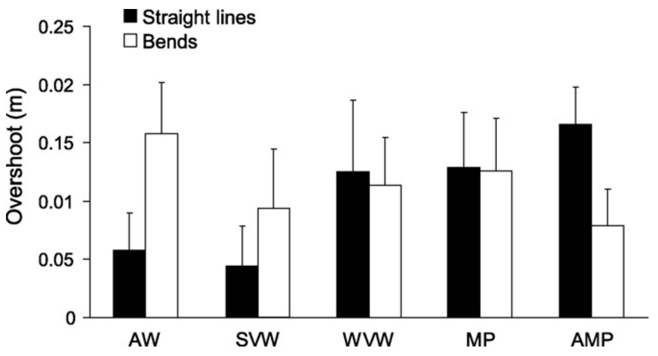

Fig. 8. Effects of all assistance devices on overshoots (maximum lateral deviation toward the borderline opposite to the initial lane departure). The 0 of the *Y* axis corresponds to the baseline obtained in WA (deviation = 0.25 and 0.31 m, respectively in straight lines and bends). Error bars represent S.E.M. *N* = 20. AW: auditory warning; SVW: seat vibratory warning; WVW: wheel vibratory warning; MP: motor priming; AMP: auditory and motor priming.

the same conclusion, although the difference between AW and MP barely failed to reach statistical significance ($p = .06$).

3.2.2. Verbal reports

3.2.2.1. Auditory warning (AW). AW gave rise to the greatest number of positive comments in the sensation category (e.g. "This one is really soft") and understanding category (e.g. "It rings on the right, it means that I have left the road on the right, it seems intuitive to me"). Fifteen out of 18 participants declared that the AW device clearly indicated the side of lane departure. Eight drivers also stated that the warning sounds referred to familiar rumble strip sounds. General attitudes and perceived utility were rather favourable, although seven drivers expressed some doubts about discerning the warning in a real vehicle environment (e.g. "I think there are already a lot of signals in the vehicle. So, how can I distinguish this one from the rest?").

3.2.2.2. Wheel vibratory warning. Nine drivers found that WVW was ineffective at clearly indicating the side of lane departure (e.g. "I felt the vibration on both hands"). Five drivers expressed the exact opposite opinion (e.g. "I knew where I left [the road] and where I needed to go"). Six drivers explained that they would be reluctant to use such a device in a real car. In addition to the lack of clarity in indicating the side of lane departure, some participants stressed a possible confusion between sensations due to the vibratory warning and steering wheel feedback from pavement-tyres contact.

3.2.2.3. Seat vibratory warning. SVW revealed a scattering of opinions. Eleven drivers perceived the lateralization of SVW without ambiguity, but it was not systematically associated with lane departure (e.g. "I know something needs to be done because of the vibration, but not necessarily what"). The general attitude was unfavourable and perceived utility was barely mentioned.

3.2.2.4. Motor priming. Although the perceived utility of the MP device was stressed by eight drivers (e.g. "The car helps me. The car shows me what to do"), eight drivers also declared that MP failed to clearly indicate the direction of lane departure (e.g. "The jolts are not indicative, it is like a back and forth movement"). In addition, MP was outlined as the most intrusive modality. Eight participants reported that they were interrupted in their steering activity when the device was active (e.g. "I had the impression I did not control the car.").

3.2.2.5. Auditory and motor priming. The combined device presented large inter-individual differences in the sensations and understanding categories. Two perceptive profiles were evidenced: those who used both auditory and haptic warnings and those who only used the most salient one ("I had the feeling I reacted because of the sound and not because of the sensation on my hands"). Eight drivers declared that they perceived one of the two signals before the other ("It was like I did not hear the sound").

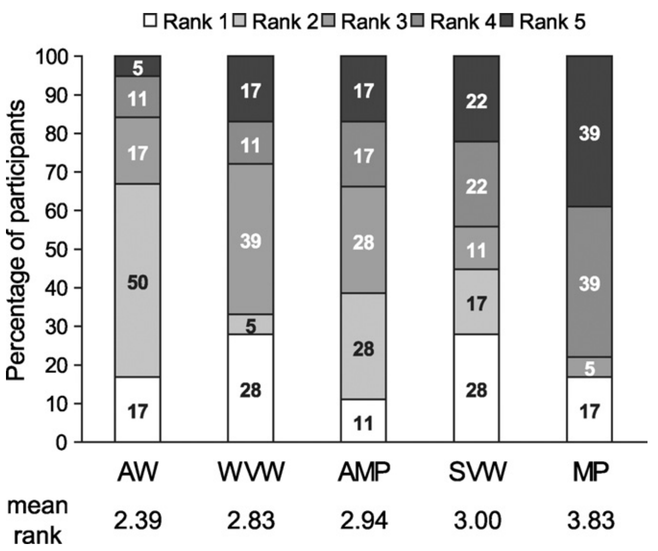

Fig. 9. Distribution of the preference rankings as a function of assistance devices ($N = 18$).

4. Discussion

Like in previous studies, warning devices were found to be effective on lateral control (Brunetti Sayer et al., 2005; Hoc et al., 2006; Navarro et al., 2007; Rimini-Doering et al., 2005; Suzuki and Jansson, 2003), but motor priming, alone or in combination with auditory warning, gave rise to significantly better recovery manoeuvres. On the other hand, the analysis of preference ranking and verbal reports showed MP was not fully accepted by drivers. The following section will discuss the determinants of the effect of MP on steering control and the nature of the dissociation between efficacy and acceptance.

MP can be described as a haptic display that delivers a directional motor prompt to the hands. The main question was to determine whether the motor component of the stimulation is sufficient to explain why MP elicits improved recovery manoeuvres. For this, MP was compared to WVW, which was identical in all points to MP except that it did not deliver a motor incentive. The results showed that both MP and AMP decreased the duration of lateral excursion and increased the sharpness of steering wheel motion more than WVW. In fact, WVW elicited lateral excursions of similar duration to those found with the other warning devices, including SVW. The latter also used the haptic modality to provide directional information but did not stimulate the hands. Incidentally, in all cases where the signal was given to the driver through the steering wheel (WVW, MP, and AMP), a small reduction in reaction time was observed. Nevertheless, considering the size of this effect ($\delta > 26$ ms), reaction times did not seem to have a substantial influence on the duration of lateral excursion. Similar to observations made by Navarro et al. (2007), the increase of steering wheel peak acceleration, which reflect the sharpness of drivers responses, appears to be the main factor in that process.

Using auditory modality rather than the haptic modality does not appear to have a significant influence on recovery manoeuvres either. AW gave rise to results very similar to those recorded for both vibratory warning devices. This supports previous studies that showed the absence of significant differences between sensory modalities in the domain of lateral control support (Navarro et al., 2007; Suzuki and Jansson, 2003). Thus, neither the fact that the stimulation was delivered to the hands through the steering wheel, nor the use of the haptic modality to convey the signal per se appear to be essential in MP. The fundamental mechanism that underlies the improved recovery manoeuvres observed with MP seems to be that the directional cue does not only improve situation diagnosis, as is the case with warning devices. It also acts directly at the motor level and prompts the driver's hands to move. These results confirm the hypothesis that in addition to improving situation diagnosis, the MP device also directly intervenes at the action level.

A legitimate question to ask about the increased sharpness of the corrective manoeuvres observed with MP would be: does it mean that steering may be too aggressive and bring about an overcorrection? Analyses of the overshoots were made in that respect. They revealed that the size of overshoot increased for all assistance devices when compared to the control condition. The only observed significant difference arose when SVW was compared to the other assistance devices. Thus, overshooting the centreline was not specific to MP. Besides, this effect was small (about 10 cm) and did not lead to the borderline being crossed on the opposite side to the initial lane departure.

The second objective of the current study was to assess drivers' acceptance. Globally, preference rankings and verbalizations were quite variable and no significant difference can be put forward. Still, our results confirm that efficiency and acceptance are not necessary correlated (Ho et al., 2006) and allow us to identify issues related to the use of the assistance devices.

The MP device, despite being the most efficient (with AMP), was ranked last in terms of preference. Interviews revealed that MP was judged to be less helpful and less acceptable than the other devices. This finding is in accordance with Kozak et al. (2006), who compared a device which applied a torque to the steering wheel to a simple vibration on the steering wheel or an auditory warning. The lower level of acceptance of MP does not appear to be related to the delivery of the signal through the steering wheel since WVW device was not perceived to be less acceptable than SVW. The interviews point to the fact that MP was seen as an intrusion in the steering activity. This element could be linked to the feeling of loss of control sometimes described in the literature (Comte et al., 2000; Young and Regan, 2007).

Conversely, participants had a more favourable attitude toward AW. The information provided by this device was perceived to be easier to identify and more useful. However, drivers' attitudes towards AW were still only slightly favourable. This result could point to the fact that drivers view LDWS unfavourably in general. This is in line with the findings of Ho et al. (2006), where drivers negatively perceived different types of alarm, including LDWS. Still, the fact that the rumble strip noise emitted by AW evoked a familiar sound seemed to play a key role in drivers' acceptance.

In terms of steering control, AMP gave rise to recovery manoeuvres which were very similar to those of MP. The advantage of MP was preserved: however it was not improved, even with the use of additional auditory information. On the other hand, an analysis of verbalizations indicates that the addition of sound may have improved acceptance of the device. Tijerina et al. (1995) reported that drivers would be willing to pay around double the price for a directional LDWS that includes both haptic and auditory modalities, rather than just one of these modalities. Our results do not indicate such an enthusiasm, since AMP was viewed less favourably than AW alone. Verbal reports indicate that this may be due to a lack of synchronization between the rumble strip sounds and the steering wheel motion. Actually, both signals were triggered at the same time, but the frequency of both signals was different. This may explain the illusion of asynchrony (auditory or haptic capture, depending on participants). Those elements led drivers to be more negative towards AMP than AW. Still, AMP was ranked higher than MP and closer to the two other devices. Consequently, this combined assistance may be a promising way to deliver both efficiency and acceptance at the same time. A replication of the experiment with a better synchronization between the two modalities will be necessary to confirm this hypothesis.

The use of driving simulation was advantageous in providing a clear assessment of the MP concept. To this purpose, the simulator was used to play highly reproducible driving scenarios and environments, in terms of weather conditions and traffic for instance. Moreover, the driving simulation was useful as it allowed exposure to repeatable critical situations (i.e. lane departures) without any harm for the participants. A strict experimental control of the lane departures was required to evaluate the effects of the various devices in comparable contexts. However, although the experiment was performed on a high performance simulator (moving base, realistic visual environment), some aspects of actual driving were missing, such as the lack of real risk and associated stress or the complexity of haptic feedback coming from the road to the steering wheel. Thus, the simulator was a relevant tool in order to design and evaluate principles of assistances devices, but assessing their benefits during real driving situations remains essential.

5. Conclusion

Despite a large variability in the way lane departures occurred, assistance devices based on the MP concept clearly remained more effective in improving recovery manoeuvres than warning devices. The results support the hypothesis of a direct intervention at the action level, whereas all other warning devices only provided assistance for situation diagnosis. However, MP devices did not act on the vehicle trajectory in the same way as LKAS. As a consequence, this device combines the advantages of LKAS (direct intervention at the action level) and LDWS (no physical correction on the car's trajectory). However, MP was less accepted by drivers than other LDWS. Associated with a more easily recognizable auditory signal, MP acceptance may be improved while maintaining its effect on steering control. A future study will focus on the optimization of the combination of both modalities.

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