Objective and subjective assessment of warning and motor priming assistance devices in car driving

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Abstract

This paper deals with moderately intrusive driving assistance devices that intervene when lane departure is imminent. A previous simulator study (Navarro *et al.*, 2007) showed that motor priming devices were more effective in assisting drivers than other lane departure warning systems. Such motor priming devices prompt the driver to take action by means of an asymmetric steering wheel vibration. This current experiment is aimed at gaining a deeper understanding of motor priming mechanisms. It raises the question of whether it is more efficient because it provides motor cuing, because it provides directional information on the steering wheel, or because the haptic modality elicits a faster response from the driver. In addition, subjective data were used to assess drivers' acceptance of the assistance devices. Results confirm that motor priming devices are more effective than auditory and vibratory warning devices during recovery manoeuvres. Neither the site of stimulation, nor the modality used for conveying information, appeared to play a significant role in the results. Interestingly, subjective data showed that drivers globally preferred auditory warning devices to motor priming devices. These results support the hypothesis that motor priming devices directly intervene at the motor level, in contrast to more traditional warning systems that act at the level of situation diagnosis.

Introduction

A significant number of all road accidents can be linked to lane departure. Bar and Page (2002) have estimated that accidents following an unintended lane departure represent about 40 percent of all crashes and about 70 percent of all road fatalities. In order to reduce the number of such accidents, various types of assistance devices are being investigated. These are expected to help drivers maintain a safe position in their lane. They rank from a simple warning when the vehicle is about to leave its lane to a complete delegation of lateral control. In all cases, cooperation between the driver and the automation will take place (Hoc, 2001). Hoc and Blosseville (2003) put forward a four-level classification system in order to categorize types of car-driving assistance within the framework of human-machine cooperation. All the driving assistance devices assessed in this study belong to the "mutual control" category, in the sense that they react to driver behaviour when the systems detect an imminent lane departure.

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The current study follows on from work carried out by Navarro et al. (2007), which assessed several assistance devices belonging to the mutual control category. In particular, it focused on the evaluation of a new type of assistance called "motor priming". Such a device triggers asymmetric steering wheel vibrations when the car is about to cross one of the lane edge lines. More precisely the device triggers alternating steering wheel motion. The first movement of the steering wheel is directed toward the road centre (side of correction), with a stronger torque and speed than the one in the direction of the side of lane departure. The aim is to provide directional information on the steering wheel without correcting the vehicle's trajectory. In this way, the device intervenes at the motor level, preactivating the corrective gesture at the proprioceptive level, without actually performing it in the place of the driver. The motor priming 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 which 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. In all cases presented, the drivers spent less time in a dangerous lateral position; however, the benefits were significantly greater with the motor priming device. This was due to an improved action on the steering wheel when the corrective manoeuvre was initiated. The results gathered by Navarro et al. (2007) support the idea that motor priming not only improves situation diagnosis, in the same way as warning systems, but also provides a motor cue to the effectors of steering control, i.e. the hands.

The main objective of this current experiment was to further investigate the determinants of benefits associated with the motor priming approach. For this, a progressive method was used which compared assistance devices which were increasingly different from the motor priming mode. The aim was to assess the relative contribution of the different characteristics which define the motor priming mode to the observed benefits on recovery manoeuvres.

The first step was to compare the motor priming mode to a lateralized vibratory warning delivered on the steering wheel. Both devices are identical (i.e. they both provide 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 enable the specific role of the motor incentive in the improvement of recovery manoeuvre. The hypothesis is that the effect of the motor priming mode at the action level mainly resides in that part of the stimulation.

Using the steering wheel to stimulate the effector of the manoeuvre may also result in faster responses from the driver. To determine the effect of the localization of the stimulus, a comparison was made between a 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 simple fact of using the haptic modality may explain some of the benefits associated with motor priming (Sklar & Sarter, 1999; van Erp & van Veen, 2004). In an attempt to isolate this dimension, the lateralized vibratory warning on the seat was compared to a lateralized warning sound.

A secondary objective of the current experiment was to assess drivers' acceptance of all the driving assistance devices in parallel with their objective effects on steering behaviour. Drivers' judgments may not favour an automation device acting on the steering wheel, even if it does not interfere with the control of the vehicle (Lefeuvre et al., 2004). It may be especially true for motor priming, due to the motor prompt. Related to this question, the combination of motor priming with a lateralized auditory warning was also studied. Navarro et al. (2007) did not observe any difference between this kind of combination and the unimodal motor priming mode when steering behaviour was analysed, but there may exist a difference in terms of acceptability. An auditory warning which mimics the sound of rumble strips was thought to be more acceptable because situation diagnosis is known to be based on the matching of the perception of an event and the previous knowledge of similar events (Wickens & Hollands, 2000). Applied to lateral control in driving assistance devices, rumble strip noise refers to well-known situations and can therefore be expected to be more acceptable. Hence, the combination of motor priming and an auditory warning of this type may form an optimal compromise between efficiency (brought about by motor priming) and acceptability (brought about by auditory warning).

Method

Participants

Four women and sixteen men 34 years of age on average (from 23 to 52 years old) were volunteered to take part in this experiment. Driving experience ranged from 4 to 35 years (16 years on the average). All of them had normal or corrected-to-normal vision. None experienced motion sickness.

Simulator

The experiment was carried out on a high-fidelity moving-base simulator (Cards2, developed by Renault's Technical Simulation Centre). The simulator constituted of a car's cockpit placed on a six-degree-of-freedom platform. The visual scene was projected onto 3 screens with 150° of visual angle. The simulator was kitted with the same equipment found in a real car, including a manual gearbox, force feedback steering wheel, pedals for brakes, accelerator and clutch, and a speedometer. The simulation was generated using the simulation software SCANeR© II (Oktal). The visual database represented a two-lane secondary road of 3.9 km in length.

Driving assistance devices

Six experimental conditions were compared in this study. All assistance devices were brought into action each time 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 rumble strip noise was played by one of the loudspeakers placed in the doors of the simulator, in the direction of lane departure.
- Seat vibratory warning (SVW): two vibrators were used, one placed in the seat and the other in the back of the seat, in the direction of lane departure.
- Wheel vibratory warning (WVW): the vibration was delivered by one of two vibrators placed in the upper part of the steering wheel (”ten-to-two” position), in the direction of lane departure.
- Motor priming (MP): a triangular asymmetric steering wheel oscillation was generated by means of two opposite impulses of different strength. The torque applied on the steering wheel was of 2 Nm was when it moved toward the road centre and of 0.5 Nm when it moved in the direction of lane departure. The period of the command signal was of 0.3 s.
- Auditory and motor priming (AMP): the AW and the MP devices were combined.
- Control condition without assistance (WA).

Reading task

Lane departures were provoked by means of a distraction task that consisted of reading a succession of words displayed through 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. During that task, the vehicle trajectory was changed slightly (drivers were unaware of this change) in order to take the car in one direction or the other. The reading task stopped (no more words on the monitor) when the vehicle reached the lateral position that triggered the driving assistance. In order to avoid too much predictability of the consequences of the distraction task, not all episodes led to lane departure.

Procedure

The study lasted about 90 minutes and consisted of 10 laps, each 3.9 km in length. Each of the five assistance devices was assessed over the course of one lap. Laps with assistance were alternated with laps without assistance. The order of presentation of the different assistance devices was fully counterbalanced between drivers. After each lap, drivers were briefly asked about the device they had just experienced.

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. Lane departure situations were provoked both in bends and straight lines. The location of these critical situations changed depending on the lap. Traffic in the opposite lane 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.

After the driving test, post-experimental interviews were conducted and drivers were asked to rank the assistance devices in order of preference (without ex-aequo).

Data analysis

To assess drivers' performance, several variables were analysed, from the moment lane departure was imminent to the moment the car returned to a normal position in the lane. The main variable was the time spent by drivers outside the safety envelope of 85 cm from the lane centre. This will be referred 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 reading task and the drivers' first action on the steering wheel. The maximum rate of steering wheel acceleration once the recovery manoeuvre was engaged was also calculated. This variable represents the strength of the steering reaction.

Each assistance device (AW, SVW, WVW, MP, and AMP) was compared to control condition (WA) by means of a Student's t-test. In order to compare the effect of the driving assistance devices, the data obtained in the control condition (WA) were subtracted trial by trial from the data obtained with assistance devices. ANOVAs were carried out on these data sets. Newman-Keuls tests were used for post-hoc comparisons. The level of significance of $p<0.05$ was used in all tests.

The order of preference given by the participants was compared across assistance devices by means of a Friedman test.

Results

Duration of lateral excursion

The duration of lateral excursion in conditions without assistance (WA) was, on average, 2.79 seconds in straight lines and 3.30 seconds in bends. In straight lines, WVW, MP and AMP significantly reduced the duration of lateral excursion (Fig. 1: WVW: $t(19)=2.31$, $p<.05$, d (size of the observed effect compared to WA) = 12%; MP: $t(19)=3.3$, $p<.01$, d=20%; AMP: $t(19)=2.81$, $p<.05$, d=15%). The effects of AW and SVW were not significant. In bends, only the effect of MP and AMP reached statistical significance (MP: $t(19)=3.38$, $p<.01$, d=21%; AMP: $t(19)=2.81$, $p<.05$, d=20%).

The ANOVA performed on the difference between conditions with assistance and WA revealed a significant effect of the assistance devices ($F(4,60)=10.04$; $p<.001$), no significant difference between bends and straight lines ($F(1,15)=.05$, ns) and no significant interaction between both variables ($F(4,60)=1.29$; ns). Post-hoc analysis indicated that MP and AMP significantly differed from all other devices ($p<.05$) and did not differ one from the other. There were also no significant differences between AW, WVW and SVW.

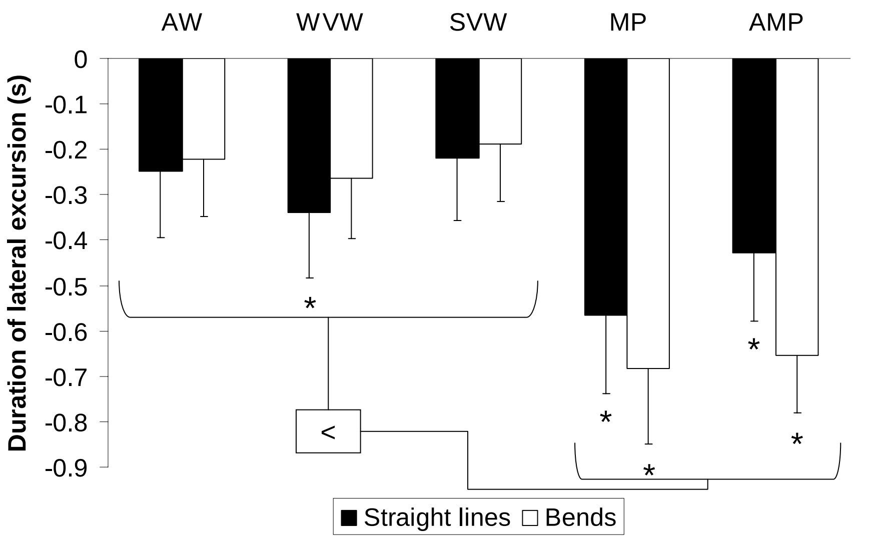

Figure 1: Effects of driving assistance devices on the duration of lateral excursion relative to the control condition. Stars represent significant differences compared to the control condition (0 on the figure). Error bars represent one standard error

Maximum rate of steering wheel acceleration

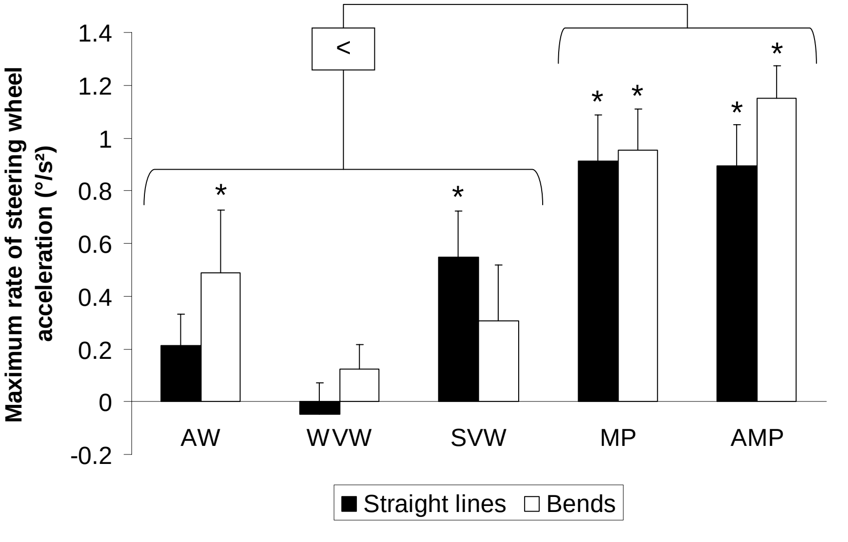

Figure 2: Effects of driving assistance devices on the maximum rate of steering wheel acceleration relative to the control condition. Stars represent significant differences compared to the control condition (0 on the figure). Error bars represent one standard error

The maximum rate of steering wheel acceleration in WA was, on average, 1.58°/s² in straight lines and 1.60°/s² in bends. In straight lines, the maximum rate of steering wheel acceleration significantly increased with SVW, MP and AMP, but not with WVW and AW (Fig. 2: SVW: $t(19)=2.2$, $p<.05$, d (size of the observed effect compared to WA) = 35%; MP: t(19)=4.87, p<.001, d=58%; AMP: t(19)=4.78, p<.001, d=57%). In bends, the maximum rate of steering wheel acceleration significantly increased with AW, MP and AMP, but not with WVW and SVW (AW: t(19)=2.26, p<.05, d=30%; MP: t(19)=6.4, p<.001, d=59%; AMP: t(19)=9.6, p<.001, d=72%).

The ANOVA performed on the difference between conditions with assistance and WA revealed a significant effect of the assistance devices (F(4,60)=20.45 ; p<.001), no significant difference between bends and straight lines (F(1,15)=0.34, ns) and no significant interaction between both variables (F(4,60)=1.79 ; ns). Post-hoc analysis indicated that MP and AMP significantly differed from all other devices (p<.05) and did not differ one from the other. There were also no significant differences between AW, WVW and SVW.

Steering reaction time

The steering reaction times in WA were, on average, 0.469 s in straight lines and 0.419 s in bends. In straight lines, none of the assistance devices significantly changed steering reaction times compared to the control condition (Fig. 3). In bends, only WVW significantly reduced steering reaction times (t(19)=2.7, p<.05).

The ANOVA performed on the difference between conditions with assistance and WA revealed a significant effect of the assistance devices (F(4,60)=3.34, p<.05), no significant difference between bends and straight lines (F(1,15)=0.07, ns) and no significant interaction between both variables (F(4,60)=0.66 ; ns). Post-hoc analysis showed the effect of assistance devices was mainly due to the WVW condition, but no difference reached statistical significance.

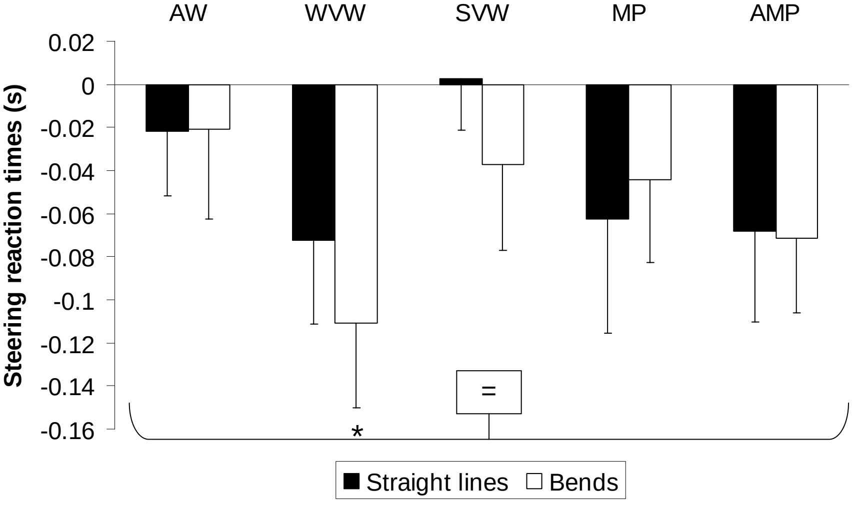

Figure 3: Effects of driving assistance devices on steering reaction time relative to the control condition. Stars represent significant differences compared to the control condition (0 on the figure). Error bars represent one standard error

Subjective data: Ranking

Fig. 4 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 test did not reveal a significant effect of driving assistance on the ranks. However, an analysis of contents tends to confirm the contrast between AW (favourable attitude) and MP (unfavourable attitude), with AMP giving rise to mixed feelings. Details about those subjective assessments can be found in El Jaafari et al. (submitted).

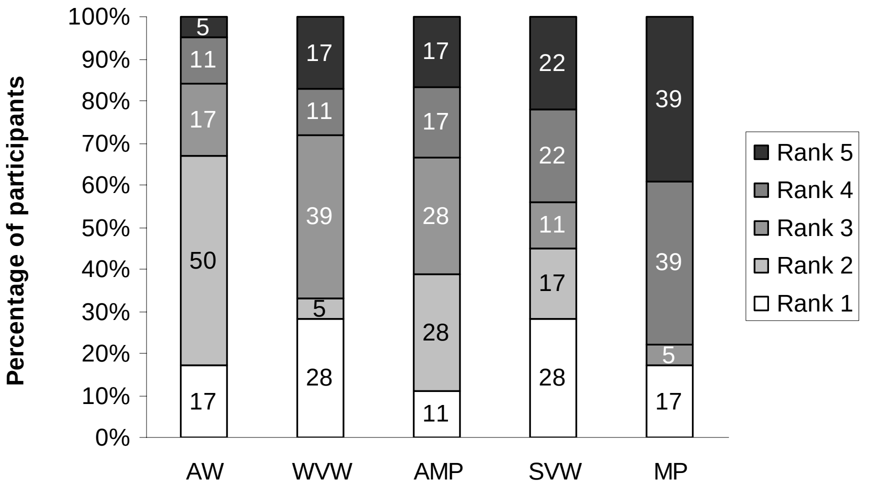

Figure 4: Proportion by rank of the relative classification in order of preference

Discussion

The global effectiveness of mutual control assistance devices was assessed through the observation of the duration of lateral excursion episodes. Only those assistance devices which gave a motor prompt to the drivers yielded a significant performance improvement in that respect. All other assistance devices (warning devices) yielded very few significant improvements compared to the control condition. The benefits associated with the MP approach did not seem to be related to a reduction of steering reaction times. They were rather due to sharper and stronger responses, as evidenced by an increased rate of steering wheel acceleration. These observations are consistent with the result of a previous study (Navarro et al., 2007). The first objective of the current experiment was to refine the understanding of the improved response associated with MP. This was done through a series of comparisons, detailed in the following discussion.

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 seems to elicit sharper responses. 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 devices with a MP component decreased the duration of lateral excursion and increased the maximum rate of steering wheel acceleration more than WVW. In fact, WVW elicited similar responses 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. If the signal was given to the driver specifically through the steering wheel, a small decrease in reaction time might be possible. Indeed, the results showed a slight tendency of WVW, MP, and AMP to reduce the time between the initiation of lane departure and the beginning of the response on the steering wheel. However, this effect was only significant for WVW in bends when compared to the control condition and no significant difference was found between assistance devices. In all cases, this effect did not influence the duration of lateral excursion. Using the haptic modality rather than audition 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 & 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.

Assistance devices which deliver motor priming were the only ones found to significantly improve recovery manoeuvres. This result contrasts with other studies where warning devices were also found to be effective (Hoc et al. 2006; Navarro et al., 2007; Suzuki & Jansson, 2003; Sayer et al., 2005; Rimini-Doering et al., 2005). A notable difference with Navarro et al. (2007) was also found concerning the motor priming modes. In that study, the average duration of lateral excursion observed in the control condition was reduced by 38 percent when MP was used. In the current study, the reduction only amounts to 19 percent. Thus, all assistance devices were globally less efficient. This is related to a large variability in the way critical situations (i.e. lane departure situations) were generated by the reading task. In Navarro et al. (2007), the critical situations were provoked by occluding the visual scene. In this study, although the distraction task gave the experiment greater ecological validity, its consequences were much less controllable. Even if the conclusion of the reading task and the triggering of assistance devices informed drivers that they had to look back at the road, drivers could be more or less reactive depending on the degree of attention paid to the reading task. Consequently, the reading task sometimes led to more serious lane departures. Nevertheless, even in these unfavourable conditions, the benefits of MP remained quite significant.

Finally, it was shown that the acceptability of the devices was not related to their efficiency in helping the driver at recovering a safe position in the lane. The way the participants ranked the assistance devices in order of preference and the analysis of post-experimental reports greatly differed across subjects. No significant difference was observed (for more details, see El Jaafari et al., submitted). However, the results tend to confirm the assumption that MP would be less accepted by drivers than a lateralized auditory warning. The combination of motor priming with a lateralized auditory warning was ranked in an intermediate position and may be a reasonable compromise between efficiency and acceptability.

Conclusion

Despite an important variability in the way lane departures occurred, assistance devices based on the motor priming concept clearly remained more effective in improving recovery manoeuvres than warning devices. The results support the hypothesis that MP devices directly intervene at the motor level, in contrast to more traditional warning systems that improve situation diagnosis. The efficiency of MP is essentially due to the incentive nature of the motor signal it delivers. On the other hand, subjective data highlighted the fact that motor priming was not well-accepted by drivers. Combining MP with a well-recognized auditory signal may be a solution to improve acceptability. Future studies where MP will be installed in real cars are now necessary to evaluate the validity of these conclusions in a more complex environment.

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