Lateral control assistance for car drivers: a comparison of motor priming and warning systems

Running title: warning and motor priming for lateral control

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ABSTRACT

Objective: This paper’s first objective is to determine whether motor priming assistance (consisting of directional steering wheel vibrations) can be of some benefit compared to more traditional auditory (lateralized sound) or vibratory (symmetric steering wheel oscillation) warning devices. We hypothesize that warning devices favor driving situation diagnosis, whereas motor priming can improve the initiation of action even further. Another objective is to assess the possible benefits of using multimodal information by combining auditory warning with simple steering wheel vibration or motor priming. Background: Within the context of active safety devices, the reported experiment dealt with moderately intrusive driving assistance devices that intervene when a certain level of risk in terms of lane departure is reached. Method: An analysis of the steering behavior of twenty participants following episodes of visual occlusion was carried out. Five warning and motor priming devices were compared. Results: All tested devices improved the drivers’ steering performance, although their effects were modulated by the drivers’ risk assessment. However, performance improvements were found to be greater with a motor priming device. No additional performance enhancement was observed when auditory warning was added to steering wheel vibration or motor priming devices. Conclusion: This study confirms the hypothesis that the direct intervention of motor priming at the action level is more effective than a simple warning, which intervenes upstream in situation diagnosis. Multimodal information did not seem to improve driver performance. Application: This study proposes a new kind of lateral control assistance, which acts at a sensorimotor level, in contrast with traditional warning devices.

INTRODUCTION

Current research into lateral control assistance ranges from devices that warn the driver when a certain level of risk is reached (Lane Departure Warning Systems: LDWS) to devices that partially contribute to steering; for example, by applying some torque on the wheel in order to bring the car back into the lane (Lane Keeping Assistance Systems: LKAS). In terms of human-machine cooperation, such devices are of a mutual control type (Hoc, 2001; Hoc & Blosseville, 2003). According to Kovordanyi et al. (2005), LDWS are assumed to improve situation diagnosis but in no way interfere with actual steering. Situation diagnosis implies that the driver must make a cognitive assessment of the situation before acting, taking into account various contextual elements. On the other hand, LKAS intervene at the action level. The driver and the automation share the steering task via the steering wheel, which means that the action of one agent directly influences that of the other (Griffiths & Gillespie, 2005). Both categories of driving assistance devices have some benefits as well as some drawbacks. LDWS are useful because they alert drivers to an approaching critical situation. The driver is in full control of the vehicle, but situation diagnosis requires some time to be achieved. On the contrary, LKAS actively contribute to steering when necessary, prompting the driver to act in order to return to a safe position in the lane. However, if the action of the device does not merge into the driver’s sensorimotor control loop, this can result in the driver reacting inappropriately. The aim of this study is to propose a device which operates somewhere between LDWS and LKAS. In other words, it provides some warning to the driver, but also intervenes at the action level. It does so with minimal interference in the steering task so as to keep the driver as the main actor within the human-machine system. The device can be described as a directional stimulation of the hands through an asymmetric vibration of the
steering wheel. More precisely, the wheel oscillates, with one direction of the oscillation being stronger than the other. This gives the impression that the wheel vibrates and “pushes” lightly toward the direction where the corrective maneuver must be performed.

Auditory warning can be given by a sound emitted from the direction of lane departure. Such devices can significantly reduce the number and duration of out-of-lane episodes (Rimini-Doering et al., 2005). A warning can also be delivered through vibro-tactile stimulation on the seat or on the steering wheel. The tactile channel may be used to provide information to the driver in a more intuitive way, at the same time releasing other heavily loaded sensory channels, such as vision or audition (Brunetti Sayer et al., 2005; Ho et al., 2005; van Erp & van Veen, 2004). However, a simple vibration on the wheel does not provide a cue as to the direction of the required lateral correction. To this end, additional visual or auditory information are needed. Redundant information presented simultaneously in different modalities has proven useful in various tasks (Spence & Driver, 2004). Within the context of in-car navigation systems, van Erp and van Veen (2004) showed that providing the same information at the same time using both auditory and visual channels can improve performance (compared to using each one separately). These types of performance enhancement were described by Wickens and Gosney (2003) as “gestalt” effects, which follow the principle that “the whole is greater than the sum of its parts”.

Suzuki and Jansson (2003) compared auditory warning (monaural or stereo) and vibratory warning devices to another type of assistance that is similar to the motor priming device in that it delivers steering torque pulses to the driver. The effects of all devices were studied on straight roads only. Large individual differences were observed. As a matter of fact, some subjects counteracted the assistance by turning the steering wheel in the wrong direction. This demonstrates that directional steering wheel stimulation can directly act at a motor level because some drivers turned the steering wheel without considering the driving context (i.e., the side of lane departure). In a test track experiment where directional auditory warning was compared to a previous version of the motor priming mode (referred to as “action suggestion”), Hoc et al. (2006) also observed larger individual differences for motor priming effects. This suggests that even very mild intrusiveness in steering control may result in negative interference for some drivers.

The main objective of this experiment was to determine in a controlled simulator setting whether or not motor priming can be achieved without negative interference, and, if some benefit was found, how this compared to more traditional auditory or vibratory warning devices. A second objective was to identify possible advantages of using multimodal information for LDWS. Here, auditory warning was combined both with simple vibratory stimulation and with motor priming.

METHOD

Participants

Twenty participants (2 females and 18 males), aged from 19 to 57 years (mean age = 25 years), with driving experience ranging from 2 to 39 years (mean = 8 years), took part in the experiment. All of them had normal or corrected-to-normal vision. None experienced motion sickness.
Simulator

This experiment took place on a fixed-base simulator (Sim², developed by INRETS-MSIS). The visual scene was projected onto a large screen (3.02 m width x 2.28 m height, about 80° x 66° of visual angle). The simulator cabin included a manual gearbox, a force feedback steering wheel, pedals for brakes, accelerator and clutch, and a speedometer. For more details, refer to Espié et al. (1999, 2003).

The visual database was a model of the GIAT test track at Satory (Versailles, France). The track is about 3.4 km in length and is similar to a two-lane main road with 14 bends and 15 straight lines (Fig. 1).

<INSERT FIGURE 1 ABOUT HERE>

Driving assistance devices

Five types of driving assistance were implemented in the simulator by MSIS. These were derived from devices that were developed by LIVIC (INRETS/LCPC laboratory, Satory, France; see Netto et al., 2003). All devices came into play when the center of the vehicle deviated more than 80 cm from the lane center. They remained active as long as the car was not driven back under this threshold.

The Auditory Warning mode (AW) was delivered by one of two loudspeakers, placed 1 m either side of the driver. The sound emitted was similar to a rumble strip noise and came from the loudspeaker on the side of lane departure.

The Vibratory Warning mode (VW) was generated by a regular triangular oscillation of the steering wheel (frequency = 5 Hz; peak-to-peak amplitude = 4°; see Fig. 2A).

The Motor Priming mode (MP) was generated by asymmetrical triangular oscillations on the steering wheel (frequency = 3.3 Hz, amplitude in the direction of lane centre = 6°; amplitude in the direction of lane departure = 3.2°, see Fig. 2B).

The Auditory and Vibratory Warning mode (AVW) was a combination of AW and VW.

The Auditory and Motor Priming mode (AMP) was a combination of AW and MP.

Finally, a condition, Without Assistance (WA), was used as the control condition.

<INSERT FIGURE 2 ABOUT HERE>

Procedure

Experimental sessions of about 90 minutes each. In the first session, participants drove for approximately 7 km in order to become accustomed to the simulator. Following this, two types of driving assistance devices were tested. In the second session, the three remaining devices were tested. In both sessions, two trials without driving assistance devices (control trial) were alternated with two trials with a driving assistance device. The functioning principle of each device was explained to the participants before they actually experienced the way it worked (self-initiated lane departure with visual control). The order of presentation of the different types of driving assistance was fully counterbalanced.

Drivers were instructed to drive in the right lane and to respect speed limits. One complete lap of the test track was performed for each trial. In the course of a trial, two unpredictable visual occlusions occurred, one before entering a bend, the other on a straight-line section (see Fig. 3 for the time course of such an event). When visual occlusion occurred, participants were asked to stop making adjustments to steering and to let the vehicle move ahead in a straight
line. Thus, visual occlusions that occurred when entering the right bend (radius: 440 m) caused a departure to the left (opposite lane) and visual occlusions that occurred when entering the left bend (radius: 130 m) caused a departure to the right (road departure, see Fig. 1). In order to standardize the direction of lane departure in straight lines, a slight shift in direction of heading (±0.9°) was introduced when the visual occlusion occurred. The driver was not aware of this change and consequently could not anticipate the direction of lane departure.

During the experiment, there were oncoming vehicles in the opposite lane. However, the experimental scenario was structured in such a way that no oncoming vehicles were present just before and after a visual occlusion. Thus, participants were never in the position of having to manage a potential collision. The visual occlusion was removed at the same time as the driving assistance device came into play, that is to say when lane departure was imminent.

Data analysis

Figure 3 describes how computed variables relate to the time course of events. In order to assess performance, the main dependent variable was defined as the time spent by drivers outside of the safety envelope of ±80 cm from the lane center after the end of the visual occlusion (Duration of Lateral Excursion, DLE). Also recorded were the steering reaction times that corresponded to the time elapsed between the end of the visual occlusion and the moment when drivers began to turn the steering wheel. Next, the maximum rate of steering wheel acceleration was used to evaluate the strength of the steering reaction: this was computed just after the visual occlusion, when the driver turned the wheel in order to bring the car back into a safe position. Finally, the overshoot toward the opposite lane edge to lane departure (i.e., the distance between the lane center and the opposite lane borderline) was computed. The data obtained in the control condition (WA) were subtracted trial by trial from the data obtained using driving assistance devices. The effects of AW, VW, MP, AVW and AMP in bends and in straight lines were then assessed for each dependent variable by repeated measures ANOVAs. Newman-Keuls tests were used for post-hoc comparisons. The level of significance of $p<0.05$ was used in all tests. These statistics were supplemented by a variant of Bayesian statistical inference (fiducial inference: see Lecoutre & Poitevineau, 1992 and Rouanet, 1996) in order to conclude on population effect ($\delta$) sizes on the basis of observed effects ($d$). In the following, statements on $\delta$ correspond to a guarantee (probability) of .90.

RESULTS

Duration of lateral excursion

Bends

On average, all devices significantly reduced the DLE in comparison to the control condition. The ANOVA revealed a significant effect of the driving assistance condition on the DLE ($F(4,60) = 5.03$, $p<.001$, Fig. 4). There was no significant difference when MP and AMP were compared. Similarly AW, VW and AVW did not differ one from another. MP and AMP gave the greatest reductions in DLE (reductions of 805 ms and 825 ms respectively compared to WA). AW, VW and AVW shortened the DLE by 391 ms on average. MP and AMP gave rise
to significantly larger effects than the other three devices (mean reduction of 425 ms, $\delta>269$ ms, $t(15) = 3.66, p<.002$). Statistics also revealed that the direction of lane departure had an influence on the effects of the assistance devices. The assistance devices resulted in a greater reduction of DLE after a left departure (towards the opposite lane) than after a right departure (road departure) ($d=280$ ms, $\delta>151$ ms, $t(15)= 2.92, p<.01$). There was no interaction between the direction of lane departure and the driving assistance conditions ($F(4,60)=0.65, p=.63$).

**Straight lines**

The statistics revealed that the effects observed in straight lines were very similar to those observed in bends. All devices significantly reduced the DLE in comparison to the control condition (Fig. 4). There was a significant main effect of the driving assistance condition on the DLE ($F(4,60)=4.12, p<.01$). There was no significant difference when MP and AMP were compared. Similarly AW, VW and AVW did not differ one from another. MP and AMP appeared to be the most effective systems, reducing the DLE by 467 ms on average. AW, VW and AVW yielded a reduction of 259 ms on average. MP and AMP gave rise to significantly larger effects than the other three devices (a mean reduction of 208 ms ($\delta>134$ ms, $t(15)=3.76, p<.002$). The direction of lane departure modified the effects of the assistance devices. Contrary to what was observed in bends, the assistance devices resulted in a greater reduction of DLE after crossing the right borderline (road departure) than after crossing the left borderline (towards the opposite lane) ($d=385$ ms, $\delta>261$ ms, $t(15)= 4.15, p<.001$). This directional effect was significantly affected by the driving assistance condition ($F(4,60)=5.19, p<.01$). Post-hoc tests showed that there was no significant difference between left and right lane departures for AW ($p=.96$). Conversely, the other systems produced different effects depending on the direction of lane departure (VW, AVW, AMP and MP: $p<.05$)

<INSERT FIGURE 4 ABOUT HERE>

**Steering reaction time**

Statistics showed a significant effect of all driving assistance devices on steering reaction times compared to the control condition. This was observed both in bends (mean observed effect ($d) = 93$ ms, $\delta>72$ ms, $t(15) = 6.06, p<.001$, Fig. 5) and in straight lines ($d=164$ ms, $\delta>144$ ms, $t(15) = 10.98, p<.001$, Fig. 5). All driving assistance devices led to a similar decrease in reaction times. Indeed, no significant difference was observed in bends ($d = 29$ ms, $|\delta|< 49$ ms, $F(4,60) = 1.63, p>.17$). In straight lines, a main effect ($d = 63$ ms, $\delta> 50$ ms, $F(4,60) = 5.52, p<.002$) was found, but post-hoc analysis revealed that only VW and AMP significantly differed one from another ($p=.04$). On average, the side of lane departure did not significantly influence the effects of assistance devices on steering reaction times, either in bends ($t(15) = 0.03, p>.97$), or in straight lines ($t(15) = 1.58, p>.13$).

<INSERT FIGURE 5 ABOUT HERE>

**Maximum rate of steering wheel acceleration**

Bends and straight lines revealed very similar patterns of results (see Fig. 6). Thus, analyzes were regrouped. All devices significantly increased the maximum rate of steering wheel acceleration. The ANOVA revealed a significant effect of the driving assistance condition on the maximum rate of steering wheel acceleration ($F(4,60)= 18, p<.001$). The effects of AW on
the maximum rate of steering wheel acceleration were significantly smaller than those observed for the other devices (\(d = 0.7^\circ/s^2, \delta > 0.58^\circ/s^2, t(15) = 7.76, p<.001\)). A comparison of MP and AMP found no significant difference. Similarly VW and AVW did not differ one from another. Once again, MP and AMP gave rise to larger effects than VW and AVW (\(d = 0.57^\circ/s^2, \delta > 0.49^\circ/s^2, t(15)=9.99, p<.001\)).

<INSERT FIGURE 6 ABOUT HERE>

Overshoot

None of the assistance devices yielded a significantly different overshoot when compared to the control condition, in bends (average decrease of 0.02m) and in straight lines (average increase of 0.08m). Moreover, no differences were found between the various devices in bends or in straight lines (\(F(4, 60) = 0.43, p>.79\) and \(F(4, 60) = 1.48, p>.22\), respectively).

DISCUSSION

The results show that all driving assistance devices clearly improved the drivers’ global performance, resulting in a significant and large reduction in the duration of lateral excursion, both in bends and in straight lines. The greatest benefits were recorded for the motor priming mode alone (MP) or with the addition of an auditory warning (AMP). MP and AMP produced an average reduction in the duration of lateral excursion of 815 ms for bends and 467 ms for straight lines. The warning modes (AW, VW and AVW) did not differ from each other and were about half as effective as the motor priming modes (MP and AMP).

A similar reduction in steering reaction times was observed in all conditions. This suggests that all driving assistance devices influenced the initiation of the corrective maneuver in a similar way. Because MP delivered quite a gentle push toward the lane center, the automated device did not artificially increase the reaction times. Thus, the benefits of MP on the global trajectory cannot be explained by a faster response.

It is possible to start differentiating between the driving assistance devices when considering the sharpness of the corrective maneuver (as evidenced by the maximum rate of steering wheel acceleration). All systems increased the strength of the response on the steering wheel, but the motor priming modes (with or without auditory warning) gave rise to sharper maneuvers than the other modes. This suggests that MP acted on the quality of the response maneuver as soon as it was initiated, and explains the global benefit of MP on the recovery maneuver. However, this increase in sharpness of the response on the steering wheel could also have resulted in some overcorrection. This was not observed, since overshoots did not differ between driving assistance devices. MP modes did not give rise to unsafe behavior.

It is important to consider that the MP devices only performed minimal corrections to the car’s trajectory. As such, they cannot be considered as a LKAS. In a situation where the driver does not hold the steering wheel (or at least holds the wheel very lightly) while slowly drifting towards the lane edge (with the axis of the car nearly parallel to the lane edge), MP might effectively bring the car back into lane, albeit slowly. However, when the driver is in control, the proper effect of MP (excluding its influence on the driver’s behavior) is negligible and cannot account for the effects reported in this experiment. This is particularly true in bends where the effects were greatest. As a matter of fact, the drivers did not perceive MP as a corrective device.
All warning devices yielded similar improvements in steering control whatever the sensory modality used and whether information about the direction of lane departure was given or not. Actually, it was observed that steering wheel corrections were a little sharper with VW (non-directional tactile stimulation) than with AW (directional auditory stimulation). However, it did not translate into a significant improvement in recovery maneuvers. Adding directional auditory information to the vibro-tactile stimulation (AVW) did not fill the gap between VW and MP. Thus, providing directional information via lateral position warning devices did not help the drivers more than non-directional signals. Suzuki and Jansson (2003) concluded similarly after observing that monaural and stereo auditory warning had comparable benefits. In all cases, the warning signals prompted the driver to take some action. The action proper was most probably performed after a situation diagnosis was carried out on the basis of the visual assessment of the environment.

The fact that auditory warning combined with MP or VW did not improve drivers’ behavior when compared to unimodal haptic devices, corresponds to the “best of both worlds” pattern described by Wickens and Gosney (2003). Whilst the particular combinations of stimuli tested in the present experiment failed to support the idea that multimodal displays are useful for assisting drivers in hazardous situations, one can argue that other configurations may be more effective in that respect.

Considering the global pattern of results, it appears that MP had a specific effect on the way the corrective maneuver was performed. We hypothesize that MP, in contrast with those devices that only provided lane departure warning, acted at the action level by providing some directional information to the hands via the haptic modality. As such, it acted at the same level of information processing as more intrusive LKAS, but with no negative interference such as counteraction or overcorrection, as previously observed. For instance, Suzuki and Jansson (2003) tested a type of driving assistance that was analogous to the MP device. They reported that some drivers countered the system, instead of turning the steering wheel in the appropriate direction. The occurrence rate of such behavior was 50% if drivers were not aware of the presence of the driving assistance device. This fell to 25% when they were aware of it. The authors compared such incorrect steering behavior with a driver’s response to a perceived lateral disturbance, such as a gust of side wind. In our study, this was not the case because none of the participants adopted an incorrect strategy. The effects of the MP device appropriately merged into the sensorimotor loop. The differences between the two studies may be due to the triangular signal form (Fig.2B) used by the MP device, which may have been smoother than the rectangular pulse-like torque used by Suzuki and Jansson (2003). It should also be noted that no difficulties could be identified in situations where participants had to act against MP to skirt round an obstacle (unpublished observations).

The hypothesis of a direct intervention at the action level does not mean that MP bypassed situation diagnosis. Just as with warning devices, drivers were able to take into account elements of the driving context whilst the car was in an unsafe position in the lane. In straight lines, the effect of the assistance devices was larger for road departure than for departure into the opposite lane. This may be explained by the fact that the driver could clearly see that there was no oncoming traffic when the visual occlusion ended. Thus, road departure was estimated to be a greater risk than driving into the opposite lane. Indeed, drivers usually avoid driving on the road shoulder because of a potential loss of adherence. In bends, the opposite effect was observed: when the car was about to leave the driving lane and enter the opposite lane (left departure), the effect of the assistance devices was a little larger than for a road departure (right departure). This apparent contradiction may be the result of the limited horizontal field of view of the driving simulator (80°). Indeed, in bends, the road ahead could only be seen for
a limited distance. Consequently, the drivers may have thought that a car could appear suddenly in the opposite lane, leaving only a few seconds to avoid a collision. So, the risk was maybe estimated to be greater when entering the opposite lane than when leaving the road, where there was no obstacle. The role of the devices was in part to inform the driver of an impending risk. A difference in the perception of risk due to the context may have modulated the effects of the assistance device on the corrective manoeuvre. Drivers modulated their behavior with warning modes as a result of risk assessment. This is not unexpected as warning modes are devoted to improving situation diagnosis. It also appears that the intervention of MP at the action level was modulated by situation diagnosis that was performed in parallel. Note, however, that the larger effects were observed on the duration of lateral excursion, which suggests that the modulation of behavior by risk assessment would mainly have taken place at the end of the recovery maneuver. In terms of risk assessment, this interpretation is speculative and should be confirmed by further studies specifically designed to test this factor.

CONCLUSION

This study suggests that MP may be more effective than traditional warning devices for the prevention of lane departure. It can be argued that this can be interpreted within the theoretical framework of a hierarchical model where action and situation diagnosis are processed in parallel. A direct intervention at the action level by an appropriate stimulation of the effectors may be the best way to facilitate efficient corrective maneuvers. Further developments of the MP device need to be carried out before considering its installation in actual cars. An important issue lies in the effects of incorrect cues (a false or missed alarm) that the device may give. Here, all driving assistance devices behaved adequately, but incorrect cues can dramatically reduce their benefits (Enriquez & MacLean, 2004). This is related to another important issue that will be explored in future experiments: the control law that determines the triggering of the automation. In the study presented in this paper, a lateral position threshold was used, but in future work, time-dependent variables such as time-to-line crossing may be assessed (van Winsum & Godthelp, 1996).

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REFERENCES


Figure 1:
Figure 2:
Figure 3:
Figure 4:

[Bar charts showing WA, VW, AVW, MP, AMP for Bends and Straight lines with index ranging from 0 to 100.]
Figure 5:
Figure 6:
Figure 1: Layout of the track. The large arrow at the bottom indicates the driving direction. The dark glasses are positioned where the visual occlusions started. The sides of possible lane departures are represented by dotted arrows. Only two visual occlusions occurred per trial.

Figure 2: The oscillations of the steering wheel for both the Vibratory Warning mode (A) and Motor Priming mode (B).

Figure 3: A representative example of the sequence of events and results recorded for a critical situation.

Figure 4: Top figures: Effects of driving assistance devices on the duration of lateral excursion relative to the control condition (WA). WA average = 1.97 sec in bends and WA average = 1.39 sec in straight lines. Error bars represent one standard error. Bottom figure: Proportional duration of lateral excursion for all driving assistance devices relative to the control condition (WA = 100).

Figure 5: Effects of driving assistance devices on steering reaction times relative to the control condition (WA). WA average = 0.45 sec in bends and WA average = 0.53 sec in straight lines. Error bars represent one standard error.

Figure 6: Effects of driving assistance devices on the maximum rate of steering wheel acceleration relative to the control condition (WA). WA average = 1.04 °/sec² in bends and WA average = 0.53 °/sec² in straight lines. Error bars represent one standard error.
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