Evaluation of human-machine cooperation applied to lateral control in car driving

J. Navarro[a], F. Mars[a], J.M. Hoc[a], R. Boisliveau[a], F. Vienne[b]

[a] *IRCCyN, CNRS and University of Nantes, B.P. 92101, 44321 NANTES Cedex 3, France*
[b] *Modélisation, Simulation et Simulateurs de conduite (INRETS – MSIS), Arcueil, France*

Abstract

Within the context of active safety devices, the reported experiment deals with unintrusive driving assistances that intervene when a given level of risk in terms of lane departure is reached. A new system designed to produce some motor priming by applying some directional vibration on the steering wheel was introduced and tested. Our main objective was to determine in a controlled simulator setting if motor priming assistance can provides some benefit compared to more traditional auditory or vibratory warning devices. The working hypothesis was that auditory and vibratory warnings would improve the situation diagnosis, whereas motor priming would additionally improve the initiation of action. Results showed that all driving assistances reduced the duration of lateral excursion after visual occlusion. Motor priming was significantly more effective in that respect compared to auditory and vibratory warning. Thus, direct intervention at the action level proved to be more efficient that a simple warning favouring situation diagnosis. Also, no performance improvement was observed when motor priming or vibratory warning were combined with auditory warning, which fails to support the idea that multimodal directional information may improve driving assistance to lateral control.

Keywords: driving assistances, lane departure warning, motor priming, auditory and haptic stimulation

1. Introduction

The development of automatic devices in order to support the driver for reasons of safety or comfort sets important questions already addressed by research on automation in the aviation domain [1]. For the moment, the main difference with aviation lies in the refusal to transform the driver into a supervisor, hence keeping the human as the main entity in charge of the driving task. Within this context, current research about assistance to the lateral control of the car ranges from devices that warn the driver when a certain level of risk is reached (Lane Departure Warning Systems: LDWS) to systems that partially contribute to steering by applying some torque on the wheel in order to bring back the car into the lane (Lane Keeping Assistance Systems: LKAS). In terms of human-machine cooperation, such systems perform mutual control [2,3]. LDWS are assumed to improve the situation diagnosis, but interfere in no way with actual steering. On the other hand, LKAS intervene at the action level. In other words, they are designed to blend with the driver's sensorimotor control processes.

Auditory warning can be given by emitting a sound on the side where the car is leaving its lane. Such devices can significantly reduce the number and length of out-of-lane episodes [4]. Warning can also be delivered with vibrotactile stimulation on the seat or on the steering wheel. The tactile channel may be used to provide information in a more intuitive way to the driver, releasing at the same time other heavily loaded sensory channels, like vision or audition [5,6,7]. Vibration delivered on the wheel may also have the advantage of directly stimulating the hands, i.e. the effectors of the required corrective manoeuvres. This may shorten reaction times, although it remains to be demonstrated. In any case, a simple vibration on the wheel does not provide cue on the direction of the required lateral correction. To this end, additional visual or auditory information would be needed.

The present work introduces a new way of prompting the driver to take action via the haptic modality. It can be described as a directional stimulation of the hands, which consists of an asymmetric vibration of the 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 in the direction where the corrective manoeuvre must be performed. This is not a LKAS proper, in the sense that its contribution to steering is minimal, but it provides some motor priming in addition to warning. Thus, it can be considered as a driving assistance at the boundary between LDWS and LKAS.

Suzuki and Jansson [8] compared auditory warning (monaural or stereo) and vibratory warning to another assistance, which was similar to the motor priming system since it delivered steering torque pulses to the driver. The effects of all devices were studied on straight roads only. When subjects were uninformed about the way the pulse-like system worked, its effect on steering was associated to large individual differences, some subject counteracting the assistance and turning the steering wheel in the wrong direction. 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 [9] also observed a larger inter-individual variability for motor priming, especially in curves. This suggests that even very mild intrusiveness in the control of steering may yield negative interference in some drivers.

The main objective of the present experiment was to determine in a controlled simulator setting whether or not motor priming can be achieved and if there is some benefit from it compared to more traditional auditory or vibratory warning devices. This was performed in curves and in straight lines.

A secondary objective was to assess the possible advantage of using multimodal information for LDWS. Indeed, redundant information presented simultaneously in different modalities has been proven useful in various different tasks [10,5]. Here, auditory warning was combined with both simple vibratory stimulation and motor priming. Both types of combinations were compared to unimodal devices.

2. Method

2.1. Participants

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

2.2. Simulator

This experiment took place on a fixed-base simulator (Sim^2, developed by INRETS-MSIS). The visual scene was projected on a large screen (3.02 x 2.28 m, 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 [11,12].

The visual database was a modelling of the GIAT test track at Satory (Versailles, France). The track is similar to a main road, including about ten bends and ten straight lines, with two opposite driving lanes.

2.3. Driving assistances

Five driving assistances, inspired by systems that were developed by LIVIC (INRETS/LCPC laboratory, Satory, France; see [13]), were implemented in the simulator by MSIS. All devices entered into action when the centre of the vehicle deviated more than 75 cm from the lane centre. 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 (the one in the direction of lane departure), placed at 1 m on both sides of the driver. The emitted sound was similar to a rumble strip noise.

The *vibratory warning mode* (VW) was generated by a regular rectangular oscillation of the steering wheel (frequency = 5 Hz; peak-to-peak amplitude = 4°).

The *motor priming mode* (MP) was generated by an 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°).

The *auditory and vibratory warning mode* (AVW) was the combination of AW and VW.

The *auditory and motor priming mode* (AMP) was the combination of AW and MP.

2.4. Procedure

Drivers were instructed to drive on the right lane of the road and to respect speed limits. One full lap of the test track was performed in each trial. In the course of a trial, two unpredictable visual occlusions occurred, one before entering a bend, the other in a straight line. Participants were asked not to perform any action on the steering wheel before the end of the visual occlusion. One of the bend was a right bend (radius: 440 m), the other a left bend (radius: 130 m). Thus, the visual occlusion caused a lane departure to the left and to the right of the driving lane, respectively. In order to standardize the direction of lane departure in straight line, a slight shift of the direction of heading (±0.9°) was introduced at the beginning of the blind period. The driver was not aware of this change and, as a consequence, could not anticipate the direction of lane departure. When lane departure did not occur in the expected direction, the trial was repeated at the end of the experimental session. The visual occlusion was removed at the same time as the driving assistance entered into action, that is to say when lane departure was imminent. After subjects got accustomed to driving the simulator, two experimental sessions of about 90 minutes each were ran. In both sessions, two trials without driving assistance (control trial) alternated with two trials with driving assistance. The order of presentation of the driving assistances was fully counterbalanced between five groups of four participants.

2.5. Data analysis

Only the most critical results will be presented here, that is those concerning the time the drivers spent outside the safety envelope of ±75 cm from the midline (duration of lateral excursion). In other words, the time between the end of the visual occlusion and the moment when the car was back to a safe position in the lane were measured and averaged across subjects. The effect of the driving assistance condition (control, AW, VW, MP, AVW, AMP) and direction of lane departure (left, right) were assessed by two repeated measures ANOVAs, one for the bends, one for the straight lines. Newman-Keuls tests were used for post-hoc comparisons. The level of significance of $p<0.05$ was used in all tests. This statistics were supplemented by a variant of Bayesian statistical inference (fiducial inference [14,15]) in order to conclude on population effect (δ) sizes on the basis of observed effects (d).

3. Results

3.1. Bends

The ANOVA revealed a significant effect of the driving assistance condition on the duration of lateral excursion ($F_{5,75}=9.47$; $p<0.001$; Fig. 1). All systems significantly reduced the duration of lateral excursion in comparison to the control condition (Table 1). There was no significant difference either between MP and AMP on the one hand, or between AW, VW and AVW on the other hand. Moreover, MP and AMP were more effective than the other systems (d=425 ms, $P(\delta>269\text{ ms})=.90$; $p<0.01$).

In the control condition, the duration of lateral excursion was nearly identical for right and left bends (1.97 s on average). However, the ANOVA revealed a global effect of the direction of lane departure: drivers returned toward the centre of the lane more quickly after a left departure than after a right departure ($F_{1,15}=9.54$; $p<0.01$; d=280 ms, $P(\delta>151\text{ ms})=.90$). Although there was no interaction between the driving assistance condition and the direction of lane departure ($F_{5,75}=1.67$; $p=0.15$), detailed statistical analyses revealed that the effect of departure direction was significant for MP and AMP ($p<0.05$). The effects observed for VW and AVW failed to reach statistical significance.

Table 1
Effects of the driving assistance systems on the duration of lateral excursion in bends.

Driving assistance	Observed effect (ms)	Population effect (ms)	Level of significance (Post-hoc)
AW	315	$P(\delta>150)=.90$	$p<0.05$
VW	487	$P(\delta>329)=.90$	$p<0.01$
MP	805	$P(\delta>624)=.90$	$p<0.001$
AVW	370	$P(\delta>193)=.90$	$p<0.05$
AMP	825	$P(\delta>648)=.90$	$p<0.001$

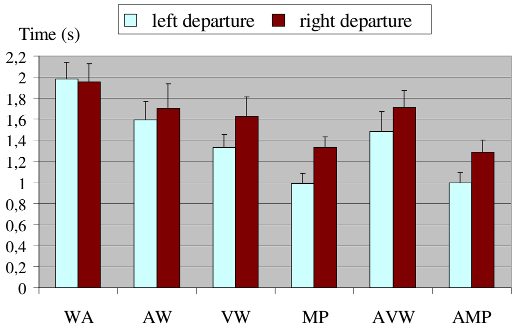

Fig. 1: Duration of lateral excursion in bends for each driving assistance conditions and both direction of lane departure. Error bars represent one standard error.

3.2. Straight lines

The ANOVA and fiducial inferences on data obtained in straight lines revealed effects of the driving assistance conditions that were very similar to those observed in bends. There was a significant main effect on the duration of lateral excursion ($F_{5,75}=9.63$; $p<0.001$). All systems significantly reduced the duration of lateral excursion in comparison to the control condition (Table 2, Fig. 2). No significant difference was observed between AW, VW and AVW on the one hand, and MP and AMP on the other hand. Moreover, MP and AMP were more effective than the other systems ($p<0.01$; d=208 ms, $P(\delta>134$ ms$)=.90$).

Table 2
Effects of the driving assistance systems on the duration of lateral excursion in straight lines.

Driving assistance	Observed effect (ms)	Population effect (ms)	Level of significance (Post-hoc)
AW	248	$P(\delta>107)=.90$	$p<0.01$
VW	248	$P(\delta>192)=.90$	$p<0.005$
MP	426	$P(\delta>307)=.90$	$p<0.001$
AVW	280	$P(\delta>212)=.90$	$p<0.005$
AMP	508	$P(\delta>419)=.90$	$p<0.001$

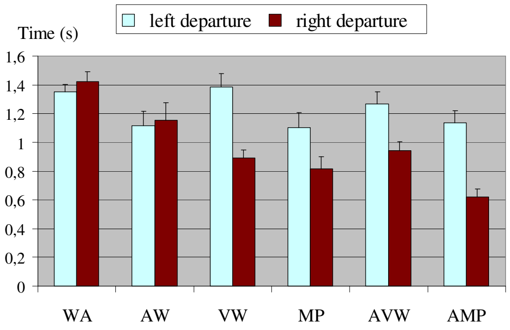

Fig. 2: Duration of lateral excursion in straight lines for each driving assistance conditions and both direction of lane departure. Error bars represent one standard error.

Statistics also revealed a main effect of the direction of lane departure: drivers returned toward the centre of the lane more quickly after crossing the right borderline than after crossing the left borderline (d=385 ms, $P(\delta>261$ ms$)=.90$, $F_{1,15}=19.28$; $p<0.001$). Moreover, a significant interaction between the driving assistance conditions and the direction of lane departure was found ($F_{5,75}=5.19$; $p<0.001$). Post-hoc tests showed that there was no significant difference between left and right departures for AW and the control condition. Conversely, the others systems yielded different effects depending on the direction of lane departure (VW, AVW, AMP: $p<0.05$; MP: $p=0.06$).

4. Discussion

All driving assistance systems improved steering performance, as evidenced by the significant reduction of the duration of lateral excursion, both in bends and in straight lines. However, the magnitude of this reduction differed across the five driving assistances. The motor priming modes (with or without added auditory warning) gave rise to faster maneuvers than warning modes. The later modes did not differ from each other.

In accordance with previous studies [4,6,8], a benefit of lateral position warning was found. The results showed that providing the direction of lane departure did not participate to this effect. Indeed, a simple unspecific vibration of the steering wheel provided similar benefits as directional auditory warning. Moreover, combining both sources of information did not reduce the duration of lateral excursion. This suggests that all warning signals improved the situation diagnosis by indicating when the car was about to cross the limit of the driving lane, but directional information was not used by the driver. Drivers most probably acted according to the visual analysis of the driving situation, when vision was recovered. A similar conclusion was formulated by [8], where monaural and stereo sounds were compared. The absence of steering improvement with redundant auditory and vibratory information also argues against the idea that multimodal displays are useful for assisting the driver in hazard situation [16].

The MP modes diminished the duration of lateral excursion by at least 363 ms in straight lines and 636 ms in bends (according to fiducial inference on the sizes of population effects, averaged across MP and AMP) compared to the control condition. In both cases, this effect was nearly the double of what was observed with the warning modes. This supports the hypothesis that providing directional cues at the motor level is more efficient for steering assistance than giving some information that requires some treatments by higher level cognitive processes.

Similarly to VW, adding direction auditory information to MP did not improve steering performance. Given the advantage of MP over AW when both systems acted separately, this is not surprising. Although MP also provided warning to the driver, it appears that the observed steering improvement was mainly due to the intervention of MP at the action level. The auditory component of AMP may have increased the situation diagnosis at the symbolic level, but, if this is true, it did not translate into an improvement of the corrective manoeuvre.

It is important to consider that the MP devices only operated minimal corrections of the car trajectory and, as such, can hardly be considered as a LKAS. In the case of a driver who do not hold the steering wheel (or hold the wheel very lightly) while slowly drifting toward the border of the driving lane (with the axis of the car nearly parallel to the edge line), MP would effectively bring the car back in the lane, although quite slowly. However, when the driver is in control the effect of MP proper (excluding its influence on the driver's behaviour) is negligible and cannot account for the effects reported in the present experiment. This is particularly true in curves where the effects were the largest. As a matter of fact, the drivers did not perceive MP like a corrective system.

Some previous studies dealing with similar driving assistance systems did not came to the same conclusion. Suzuki and Jansson [8], using pulse-like steering torque, observed incorrect strategies in some drivers, who turned the steering wheel in the opposite direction (i.e. in the direction of lane departure) as if to compensate for the torque generated by the device. This kind of behaviour occurred in 50% of the drivers when they were not informed of the meaning of driving assistance and in 25% of subjects when they were informed. The authors interpreted the incorrect motor response as a reaction to a perceived lateral disturbance such as a side gust. This suggests that the action of the driving assistance did not blend in the sensorimotor control loop. As a consequence, it was most probably felt as intrusive and produced some counteracting steering behaviour. This was not the case with the MP devices (where participants were informed of the driving assistance meaning) since none of the participants adopted an incorrect strategy.

All driving assistances except AW were affected by the direction of lane departure. However, this effect was opposite for bends and straight lines. In bends, when the car was about to leave the driving lane and enter the opposite lane (left departure), the effect of the assistances was a little larger than for a road departure (right departure). This is possibly due to the fact that, in bends, there was reduced visibility of the adverse traffic (risk of collision). Thus, the risk was probably estimated as higher when entering the opposite lane than when leaving the road, where there was no obstacle. On the other hand, the effect of the assistances was larger in straight lines for road departure than for lane departure into the opposite lane. This can be explained by the fact that there was no adverse traffic when the visual occlusion ended. Thus, the risk was most probably estimated as higher for road departure than for driving into the opposite lane. These results suggest that the appreciation of the risk by the driver can influence the effect of the assistances.

5. Conclusion

As expected the motor priming assistance, alone or in combination with the auditory warning assistance, significantly improved steering during a recovery manoeuvre in comparison with assistances that only provided some kind of warning. This supports the hypothesis that a direct intervention in the sensorimotor control processes (subsymbolic processes) can help steering in a lane departure situation more efficiently than a simple warning that improves the situation diagnosis (symbolic processes).

Future research will aim at validating this conclusion. One main concern will be to improve ecological validity of the experiments, in particular by using a more realistic lateral disturbance, such as a simulated wind gust or loss of adherence. Indeed, the visual occlusions informs the driver that a lane departure is imminent, which may influence the effects of the driving assistances. Also, in the present experiment, the driving assistances entered into action when threshold in terms of lateral position was reached. More complex risk functions taking into account lateral speed or time to lane crossing will be used in the future. Finally, the validation of the MP concept in real driving condition will be considered.

Acknowledgements

This study has been supported by the European Program PREVENT (SafeLane) and by the French Program PREVENSOR (ANR-PREDIT). The authors are thankful to Elise Jolly for her technical assistance.

References

[1] Stanton NA, Young MS, Walker GH, Turner H and Randle S. Automating the driver's control tasks. Int. J. Cogn. Ergonom. 5 (2001) 221-236.

[2] Hoc JM. Towards a cognitive approach to human-machine cooperation in dynamic situations. Int. J. Hum.-Comput. St. 54 (2001) 509-540.

[3] Hoc JM and Blosseville JM. Cooperation between drivers and in-car automatic driving assistance. Proc. CSAPC, 2003, pp. 17-22.

[4] Rimini-Doering M, Altmueller T, Ladstaetter U and Rossmeier M. Effects of lane departure warning on drowsy drivers' performance and state in a simulator. Proc. Driving Assessment, 2005, pp. 88-95.

[5] Van Erp JBF, Van Veen HAHC. Vibrotactile in-vehicle navigation system. Transport. Res. F. 7 (2004) 247-256.

[6] Brunetti Sayer T, Sayer JR, Devonshire JM. Assessment of a Driver Interface for Lateral Drift and Curve Speed Warning Systems: Mixed Results for Auditory and Haptic Warnings. Proc. Driving Assessment, 2005, pp. 218-224.

[7] Ho C, Tan HZ, Spence C. Using spatial vibrotactile cues to direct visual attention in driving scenes. Transport. Res. F. 8 (2005) 397–412.

[8] Suzuki K, Jansson H. An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system. Jap. Soc. Automotive Eng. Rev. 24 (2003) 65-70.

[9] Hoc JM, Mars F, Milleville-Pennel I, Jolly E, Netto M, Blosseville JM. Evaluation of human-machine cooperation modes in car driving for safe lateral control in bends: function delegation and mutual control modes. Trav. Humain. (in press).

[10] Spence C, Driver J. Crossmodal space and crossmodal attention, Oxford University Press, New York, 2004.

[11] Espié S, Mohellebi H, Kheddar A. A high performance / low-cost mini driving simulator alternative for human factor studies. Proc. Driving Simulation Conference, 2003.

[12] Espié S. Vehicle-driven simulator versus traffic-driven simulator: the INRETS approach. Proc. Driving Simulation Conference, 1999.

[13] Netto MS, Labayrade R, Ieng SS, Lusetti B, Blosseville JM, Mammar, S. Different Modes on Shared Lateral Control. 10th ITS World Congress, Madrid, Spain, 16-20 Nov, 2003

[14] Lecoutre B, Poitevineau J. Programme d'Analyse des Comparaisons (PAC) [Comparison Analysis Program]. Saint-Mandé, France: CISIA, 1992.

[15] Rouanet H. Bayesian methods for assessing importance of effects. Psychol. Bull., 119 (1996) 149-158.

[16] Seppelt B, Wickens CD. In-Vehicle Tasks: Effects of Modality, Driving Relevance, and Redundancy. Technical Report AHFD-03-16/GM-03-2 (General Motors Corporation), 2003.