A COMPARISON OF WARNING AND MOTOR PRIMING ASSISTANCE SYSTEMS FOR LATERAL CONTROL IN CAR DRIVING

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Abstract

In order to prevent lane departures in car driving active safety devices have been developed. This paper assesses a new system designed to produce some motor priming (consisting of directional steering wheel vibrations) when a car is at risk of lane departure. The first objective was to determine if motor priming assistance can be of some benefit compared to more traditional auditory (lateralized sound) or vibratory (symmetric steering wheel oscillation) warning devices. Whilst on the one hand the motor priming mode was assumed to operate at the action level, on the other hand, other tested driving assistance devices were assumed to favour driving situation diagnosis. The second objective was to assess the possible advantage of using multimodal information by combining auditory warning with simple steering wheel vibration and motor priming. Observed behaviours showed that all tested devices improved drivers' steering performance; however, performance improvements were greater with a motor priming system. No performance enhancement was recorded when steering wheel vibration or motor priming systems were combined with auditory warning. This study confirms our hypothesis that the direct intervention of motor priming on motor action preparation is more effective than a simple warning which favours situation diagnosis. Multimodal information did not seem to improve drivers' performance in driving assistance systems for lateral control.

Résumé

Dans l'objectif d'améliorer la prévention des sorties de voie, différentes assistances à la conduite avertissant d'une position latérale sur la voie risquée, ont été développées. Un nouveau type d'assistance appelé « amorçage moteur » consistant en une vibration asymétrique de la colonne de direction du véhicule lors d'un écart au centre de la voie trop important a été testé. L'objectif principal était d'évaluer l'effet de ce nouveau mode d'assistance en comparaison à des assistances plus traditionnelles telles qu'une vibration symétrique de la colonne de direction ou d'un son indiquant le côté de sortie de voie. L'assistance « amorçage moteur » est présumée agir directement au niveau de la réalisation de l'action tandis que les autres assistances devraient favoriser le diagnostic de la situation de conduite. Notre objectif secondaire était d'évaluer le bénéfice potentiel de la multimodalité des assistances à la conduite. Cette hypothèse a été testée en combinant un son indiquant le côté de sortie de voie avec la vibration symétrique du volant d'une part et avec l' « amorçage moteur » d'autre part. Les résultats observés montrent que l'ensemble des assistances testées produisent une amélioration de la performance de conduite. Cette amélioration était toutefois nettement plus importante avec l'assistance « amorçage moteur ». Aucune amélioration de performance n'a été enregistrée pour les deux modes combinés infirmant ainsi l'éventualité d'un bénéfice de la multimodalité. L'hypothèse d'un effet direct de l'assistance « amorçage moteur » sur la préparation de l'action motrice semble être confirmée. Il en est de même pour l'hypothèse d'une amélioration du diagnostic de la situation concernant les autres assistances à la conduite.

Introduction

Run-off-road departures make up a considerable proportion of all road accidents. In 2002, Bar and Page reported than 35% to 70% (according to the type of indicator) of all French road accidents had their roots in lane or road departure. In order to reduce the number and severity of vehicle accidents, automatic devices have been developed. The first lateral control device devoted to lane departure prevention was ESP (Electronic Stability Program). This has been available in French cars since the early 2000s. The major benefit of ESP was seen to be in critical situations, such as car skids or when drivers do not brake adequately in a bend (see Page & Cuny, 2006, for an analysis of accidents with ESP). In this paper, we look at other kinds of automatic devices that are expected to help drivers just before a critical situation (imminent lane departure) detected by the device. The introduction of such automatic devices that belong to mutual control (Hoc, 2001; Hoc & Blosseville, 2003) raises important questions for the field of human-machine cooperation.

Within this context, current research about lateral control assistance 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 the car back into lane (Lane Keeping Assistance Systems: LKAS). According to Kovordanyi et al. (2005), on the one hand 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; this means that both the driver and the automation act on steering.

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 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, such as vision or audition (Brunetti Sayer et al., 2005; Ho et al., 2005; van Erp & van Veen, 2004). Vibration delivered on the wheel may also have the advantage of directly stimulating the hands, that is to say the effectors of the required corrective manoeuvres. This may shorten reaction times, although this remains to be demonstrated. In any case, a simple vibration on the wheel does not provide a cue on the direction of the required lateral correction. To this end, additional visual or auditory information would be needed.

This paper 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 properly an LKAS in the sense that its contribution to steering is minimal. It does, however, provide some motor priming in addition to warning the driver. Thus, it can be considered as a driving assistance system somewhere between LDWS and LKAS.

In 2003, Suzuki and Jansson compared auditory warning (monaural or stereo) and vibratory warning device to another type of 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 not informed about the way the pulse-like system worked, its effect on steering was associated with large individual differences, indeed some subjects 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. (2006) also observed larger individual differences for motor priming effects. These two studies argue in favour of a direct intervention of the motor priming mode on motor control even though this sometimes negatively interferes with some drivers' steering.
The main objective of this experiment was to use a controlled simulator setting to determine whether or not motor priming could be achieved and if so, whether there would be some benefit from it compared to more traditional auditory or vibratory warning devices. This experiment used both bends and straight lines.
A secondary objective was to assess the possible advantages of using multimodal information for LDWS. Indeed, redundant information presented simultaneously in different modalities has been proven useful in various tasks (Spence & Driver, 2004; van Erp & van Veen, 2004). Here, auditory warning was combined with both simple vibratory stimulation and motor priming. Both types of combinations were compared to unimodal devices.

Method

Participants

Twenty participants (2 women and 18 men aged between 19 and 57 years (25 years on average), and with driving experience ranging from 2 to 39 years (8 years on average) took part in this experiment. All of them had normal or corrected-to-normal vision.

Simulator

This experiment took place on a fixed-base simulator (Sim^2, developed by INRETS-MSIS). The visual scene was projected onto 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 Espié et al. (1999) and Espié et al. (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 (Fig. 1).

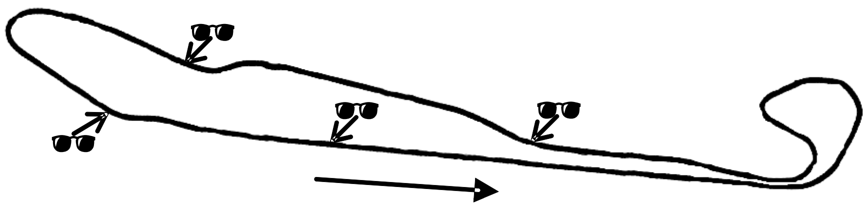

Fig. 1: Layout of the track used during the experiment. The arrow indicates the driving direction and the dark glasses point to where the visual occlusions start (see below).

Driving assistance devices

Five types of driving assistance, inspired by systems that were developed by LIVIC (INRETS/LCPC laboratory, Satory, France; see Netto et al., 2003), were implemented in the simulator by MSIS. All devices came into play when the centre of the vehicle deviated more than 80 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, placed at 1 m either side of the driver. The emitted sound was similar to a rumble strip noise and came from the loudspeaker facing the direction of lane departure.
The *vibratory warning mode* (VW) was generated by a regular rectangular 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.

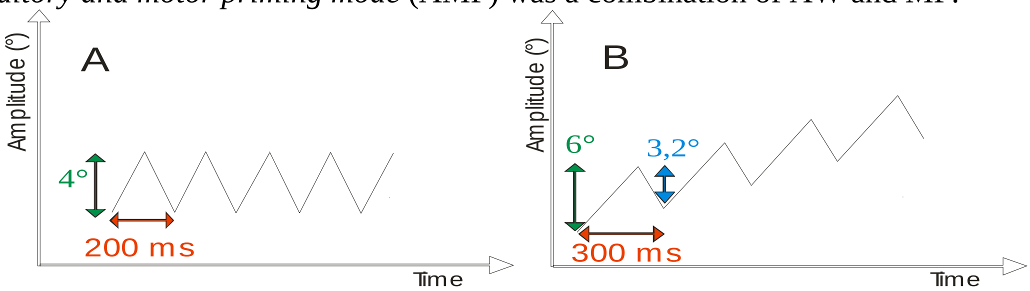

Fig.2 : The oscillations of the steering wheel without any force applied on the direction column for both Vibratory Warning mode (A) and Motor Priming mode (B).

Procedure

Drivers were instructed to drive in the right-hand lane and to respect speed limits. One full 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 (Fig.1). Participants were asked not to make any movement on the steering wheel before the end of the visual occlusion. One of the bends was a right bend (radius: 440 m), the other a left bend (radius: 130 m). Thus, the visual occlusion caused a departure to the left and to the right of the driving lane, respectively. In order to standardize the direction of lane departure a slight shift in direction of travel (±0.9°) was introduced at the beginning of the blind section. The driver was not aware of this change and, as a consequence, could not anticipate the direction of lane departure. 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. Subjects first became accustomed to driving the simulator before participating in two experimental sessions of about 90 minutes each. In both sessions, two trials without driving assistance devices (control trial) were alternated with two trials with a type of driving assistance. The order of presentation of the different types of driving assistance was fully counterbalanced.

Data analysis

The results relating to the time the drivers spent outside the safety envelope of ±80 cm from the midline (duration of lateral excursion) were analysed. In other words, the time elapsed between the end of the visual occlusion and the moment when the car was back to a safe position in the lane was measured. The second variable of interest was the maximum rate of steering wheel acceleration. This occurs after the visual occlusion, when the driver turns the wheel sharply in order to bring back the car back into a safe position in the lane. The effects of the driving assistance condition (control called without assistance (WA), AW, VW, MP, AVW, AMP) were assessed by four repeated measures ANOVAs, one for the bends and one for the straight lines for each dependant variable. Newman-Keuls tests were used for post-hoc comparisons. T-test comparisons were also used in order to compare regrouped driving assistance modes. The level of significance of $p<0.05$ was used in all tests. Some inferences on size effects were made on the basis of the observed effects; however, further statistical details (fiducial inference) on the duration of lateral excursion can be found in Navarro et al. (in press).

Results

Bends

Duration of lateral excursion in 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. 3A). All systems significantly reduced the duration of lateral excursion in comparison to the control condition. The MP and AMP gave the greatest reduction of lateral excursion duration (reductions of 805 ms and 825 ms respectively compared to WA). The AW, VW and AVW modes were not significantly different and shortened the duration of lateral excursion by 391 ms on average. There were no significant differences between MP and AMP on the one hand and between AW, VW and AVW on the other hand. In addition, MP and AMP were significantly more effective than other systems (mean reduction of 425 ms; $t(19) = 3.65$; p<0.01).

Maximum rate of steering wheel acceleration in bends

Statistics showed that every system except AW had a significant effect on maximum rate of steering wheel acceleration ($F_{5,75} = 27.56$; $p<0.001$; Fig. 3B). Indeed all systems increased maximum rate of steering wheel acceleration, although once again the MP and AMP modes were the most effective systems. There appeared to be no significant difference between these two systems; they both led to an average increase of more than twice the maximum rate of steering wheel acceleration compared to the control condition (WA). Moreover, MP and AMP regrouped gave a maximum rate of steering wheel acceleration significantly greater than those observed for all other systems regrouped ($t(19) = 8.83$; $p<0.001$). There was no significant difference either between AW and VW ($p<0.07$) on the one hand, or between VW and AVW ($p<0.13$) on the other hand. However, AW and AVW were significantly different ($p<0.01$). To sum up, AW seemed to be the less effective system, at least from the maximum rate of steering wheel acceleration point of view.

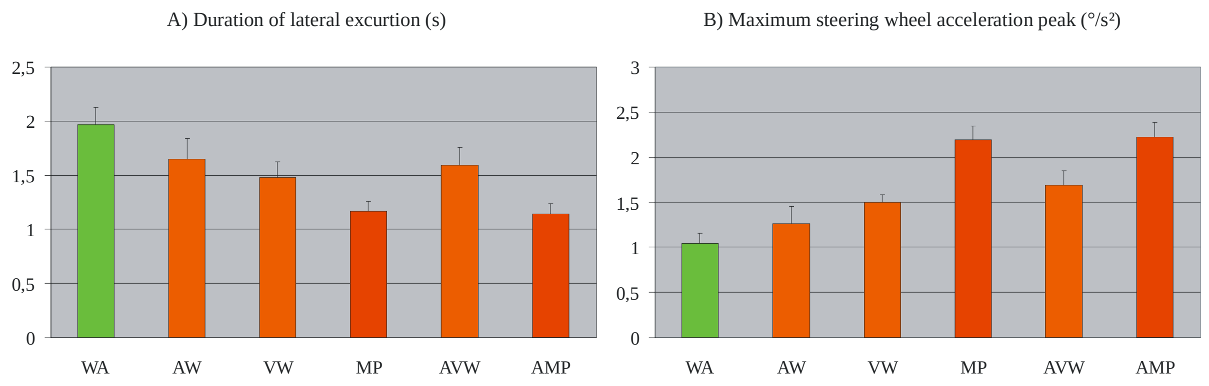

Fig. 3: Duration of lateral excursion (A) and maximum rate of steering wheel acceleration (B) in bends without assistance and for each driving assistance type. Error bars represent one standard error.

Straight lines

Duration of lateral excursion in straight lines

The ANOVA performed on data for the duration of lateral excursion in straight lines revealed that the effects of the driving assistance conditions 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 (Fig. 4A). No significant difference was observed between AW, VW and AVW on the one hand, and MP and AMP on the other hand. As observed in bends, MP and AMP appeared the most effective, reducing the duration of lateral excursion by 467 ms on average. Although the other systems were less efficient, they nevertheless allowed a reduction of 259 ms on average. The observed effect between MP combined with AMP and others systems put together was of 208 ms ($t(19) = 3.82$; $p<0.01$).

Maximum rate of steering wheel acceleration in straight lines

As far as the duration of lateral excursion is concerned, the ANOVA revealed that the effects on maximum rate of steering wheel acceleration were similar for bends and straight lines. Indeed, the statistics show that each system had a significant effect on maximum rate of steering wheel acceleration ($F_{5,75} = 47.48$; $p<0.001$; Fig. 4B). Each system significantly increased the maximum rate of steering wheel acceleration. On the contrary of maximum rate of steering wheel acceleration on bends, AW was significantly different from each other systems. Of all the modes, AW system had the smallest (but significant) increased effect on maximum rate of steering wheel acceleration. Again, MP and AMP were not significantly different and this was also the case for VW and AVW. The MP and AMP modes were still more efficient than the VW and AVW modes ($t(19) = 5.09$; $p<0.001$).

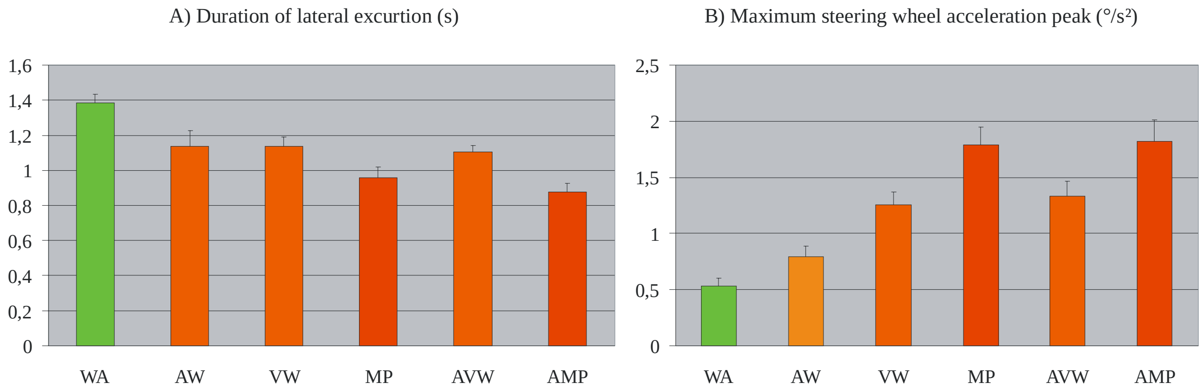

Fig. 4: Duration of lateral excursion (A) and maximum rate of steering wheel acceleration (B) in straight lines without assistance and for each driving assistance type. Error bars represent one standard error.

Discussion

All of the driving assistance systems increased participants' performance, assessed by the significant reduction in the duration of lateral excursion and an increase in maximum rate of steering wheel acceleration. The motor priming modes (with or without added auditory warning) gave rise to faster and stronger maneuvers than other modes. This was observed for the duration of lateral excursion and the maximum rate of steering wheel acceleration respectively. The benefits of the motor priming modes were clear for the two variables in bends and in straight lines.

As was found in previous studies (Brunetti Sayer et al., 2005; Rimini-Doering et al., 2005), a lateral position warning was seen to have benefits. The results for the duration of lateral excursion showed that indicating the direction of lane departure did not participate in this effect. Indeed, a directional auditory warning gave similar results to a simple unspecific vibration of the steering wheel. Suzuki and Jansson (2003) reported a similar conclusion. In their study, monaural and stereo sounds had comparable effects on drivers. The absence of any improvement when lateralized auditory and unspecific steering wheel vibrations were combined reinforced the idea that lateralized information was not used by drivers. Such types of driving assistance (AW, VW and AVW) served to warn the driver when the car was about to cross the limit of the driving lane. The steering wheel corrections were however slightly stronger (according to maximum rate of steering wheel acceleration) when the steering wheel vibration system was used compared to auditory warning. This result, although not significant between AW and VW in bends, may be due to direct stimulation on the effectors (i.e. the hands). In any case, the duration of lateral excursion was not affected by the stronger response made by the driver after a vibratory warning. This was probably due to a stronger but shorter steering wheel rotation after a vibratory warning than an auditory warning.

The MP and AMP modes produced an average reduction in the duration of lateral excursion of 815 ms for bends and 467 ms for straight lines, and an average increase in maximum rate of steering wheel acceleration of 213% for bends and 340% in straight lines; global comparisons were made with the control condition (WA). In addition, the MP modes were about twice more effective than the warning modes both in term of duration of lateral excursion and steering wheel response strength (measured by the maximum rate of steering wheel acceleration). This comparison supports the hypothesis that driving assistance systems with a direct action at a motor level have a greater effect than warning assistance systems which only improve situation diagnosis.

As observed for AVW, no significant improvement in performance was found for the combination of MP with AW. In comparison with MP alone, the multimodal display (AMP) did not improve the driver’s performance. In the present driving context, no “gestalt” effect was found: this was defined by Wickens and Gosney (2003) as: “the whole is greater than the sum of its parts”. Nevertheless, our results do correspond to the “best of both worlds” pattern described by Wickens and Gosney. Indeed, the redundant display (i.e. the AMP mode) produced a performance that was equal to the better of the two single-modality conditions (i.e. the MP mode). The fact that there was no steering improvement with redundant auditory and vibratory (with or without priming) information contradicts the idea that multimodal displays are useful for assisting drivers in hazardous situations (Seppelt & Wickens, 2003). In the case of the AMP mode, the absence of a redundant display has benefits which are the result of a direct intervention at the action level for MP together with a parallel driving situation diagnosis improvement. As a consequence, it came as no surprise to observe that steering performance was only improved by MP. To conclude, with regard to the multimodality question the combination of VW and AW was quite different from the AMP combination. The AVW combination regrouped two warning systems (instead of warning plus motor priming for the AMP mode). However, our results showed that only one of the two warning systems was needed to inform the driver of an imminent lane departure.

It is important to consider that the MP devices only performed minimal corrections to the car’s trajectory: as such, they can hardly be considered as an LKAS. In a situation where the driver does not hold the steering wheel (or indeed 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 would effectively bring the car back into the lane, albeit slowly. However, when the driver is in control, the proper effect of MP (excluding its influence on the driver's behaviour) 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 system.
Suzuki and Jansson (2003) tested a driving assistance analogous to the MP system used in the present study. The system assessed by these authors produced a pulse-like steering torque in the direction of the lane centre. The authors reported that some drivers, instead of turning the steering wheel in the direction indicated by the system, countered this system. As a result, these drivers turned the wheel in the direction which would lead to lane departure; this behaviour was called "incorrect strategy". In Suzuki and Jansson's study, the occurrence of such behaviour was of 50% if drivers were not aware of the presence of the driving assistance and fell to 25% when they were aware of it. The authors interpreted this incorrect motor response as a response to a perceived lateral disturbance such as a gust of wind from the side. Consequently, driving assistance was misunderstood at a sensori-motor level. This was not the case in the present study because none of the participants adopted an incorrect strategy. The effects of MP on performance suggested that the system was merged into the sensorimotor loops.

Conclusion

As expected, the motor priming assistance device, alone or in combination with the auditory warning assistance device, had a very large effect in comparison with other types of assistance (auditory or vibratory warning on the steering wheel and a combination of both). This study confirms our hypothesis that a direct intervention on motor action preparation is more effective than a simple warning which favours diagnosis. However, the use of an assistance device which combines information at both an action and diagnosis level (motor priming with auditory warning) did not improve performance. The assumption of two levels (action and diagnosis) of parallel information processing was proposed.
Visual occlusion was used to standardize the time and place of lane departure. However, the black screen (which corresponds to visual occlusion) on its own provided information by drawing the drivers' attention. In order to simulate a common lateral disturbance, a side gust of wind or a partial loss of road adherence could be used in future experiments. It is also necessary to refine the threshold of the assistance trigger. As a consequence, the development of devices which take into account the speed of lateral gap reduction or the time to lane crossing appears to be of some importance.

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