Lateral Control Assistance for Car Drivers: A Comparison of Motor Priming and Warning Systems

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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 with 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 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 20 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

Methods of lateral control assistance that are currently being studied range from devices that warn the driver when a certain level of risk is reached (lane departure warning systems: LDWSs) 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: LKASs). In terms of human-machine cooperation, such devices are of a mutual control type (Hoc, 2001; Hoc & Blosseville, 2003).

According to Kovordányi, Ohlsson, and Alm (2005), LDWSs 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, LKASs 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. LDWSs 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, LKASs actively contribute to steering

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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 that operates somewhere between an LDWS and an LKAS. In other words, it provides some warning to the driver, but it 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, Altmueller, Ladstaetter, & Rossmeier, 2005). A warning can also be delivered through vibrotactile 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 (Ho, Tan, & Spence, 2005; Sayer, Sayer, & Devonshire, 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 is 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 with 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 with 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 participants 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 in which directional auditory warning was compared with 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 with more traditional auditory or vibratory warning devices. A second objective was to identify possible advantages of using multimodal information for LDWSs. Here, auditory warning was combined both with simple vibratory stimulation and with motor priming.

METHOD

Participants

Twenty participants (2 women and 18 men), 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 (SIM^2, developed by the Modélisation, simulation et simulateurs de conduite research department of the Institut national de recherche sur les transports et leur sécurité [INRETS-MSIS]). The visual scene was projected onto a large screen (3.02 m width × 2.28 m height; about 80° × 66° of visual angle). The simulator cabin

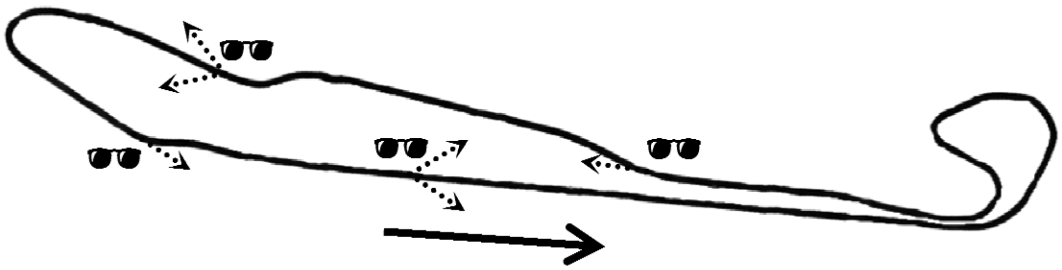

Figure 1. Layout of the track. The large arrow at the bottom indicates the driving direction. The dark glasses are positioned where the visual occlusions started. The sides of possible lane departures are represented by dotted arrows. Only two visual occlusions occurred per trial.

included a manual gearbox; a force feedback steering wheel; pedals for brakes, accelerator, and clutch; and a speedometer. For more details, refer to Espié (1999).

The visual database was a model of the GIAT (Groupement industriel des armements terrestres) 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 (Figure 1).

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 (Laboratoire sur les interactions véhicules-infrastructures-conducteurs) (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* (AW) mode was delivered by one of two loudspeakers placed 1 m on 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* (VW) mode was generated by a regular triangular oscillation of the steering wheel (frequency = 5 Hz; peak-to-peak amplitude = 4°; see Figure 2a).

The *motor priming* (MP) mode was generated by asymmetrical triangular oscillations on the steering wheel (frequency = 3.3 Hz; amplitude in the direction of lane center = 6°; amplitude in the direction of lane departure = 3.2°; see Figure 2b).

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

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

Finally, a condition *without assistance* (WA) was used as the control condition.

Procedure

The experiment consisted of two sessions of about 90 min 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

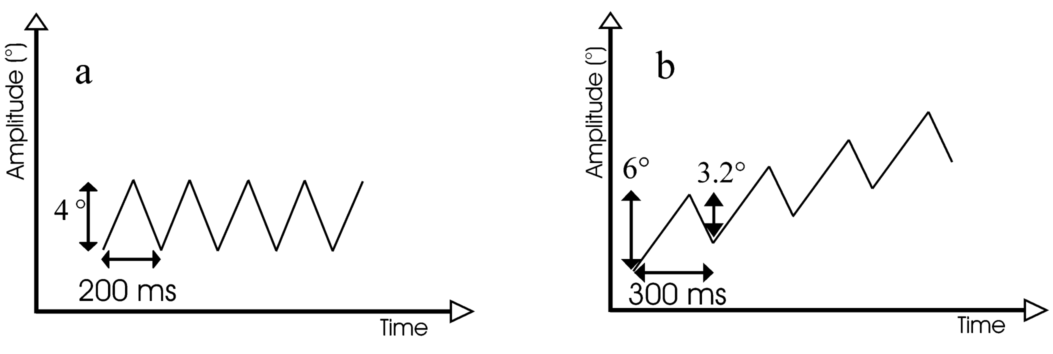

Figure 2. The oscillations of the steering wheel for (a) the vibratory warning mode and (b) the motor priming mode.

tested. In the second session, the three remaining devices were tested. In both sessions, two trials without driving assistance devices (control trials) 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 (one 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 Figure 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 Figure 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 (at a rate of approximately 3–4 vehicles/km of roadway and at a speed of 60 km/h). 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, we defined the main dependent variable as the time spent by drivers outside 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

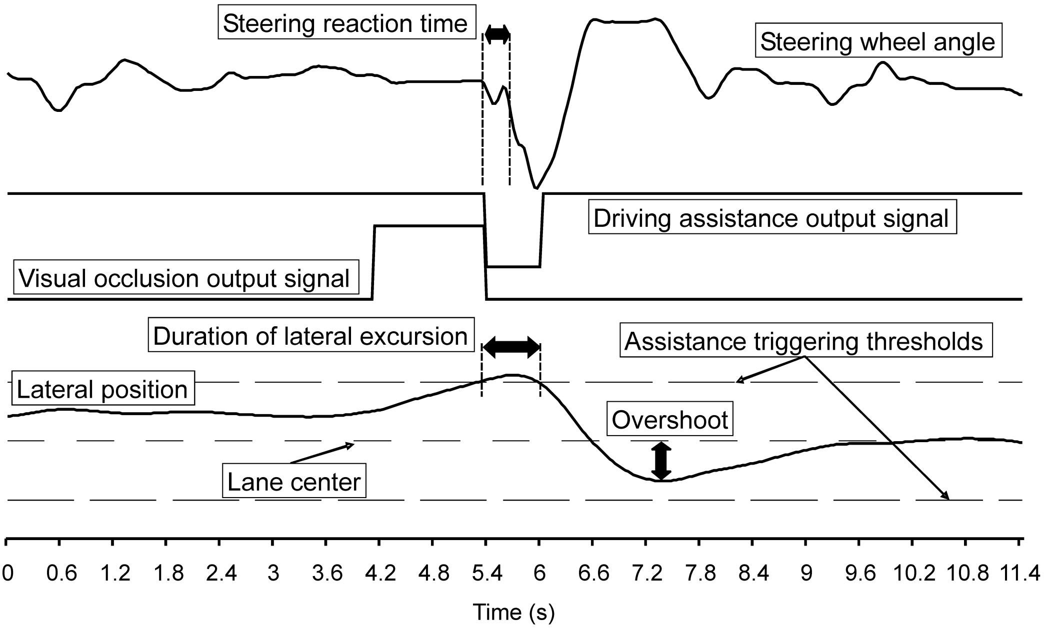

Figure 3. A representative example of the sequence of events and results recorded for a critical situation.

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 maximum lateral position toward 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 $p < .05$ 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 emit a probabilistic judgment on the population effect (δ) sizes on the basis of observed effects (d). In the following, statements on δ correspond to a guarantee (probability) of .90.

RESULTS

Duration of Lateral Excursion

Bends. On average, all devices significantly reduced the DLE in comparison with the control condition. The ANOVA revealed a significant effect of the driving assistance condition on the DLE, $F(4, 60) = 5.03$, $p < .001$ (Figure 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 and 825 ms, respectively, compared with WA). AW, VW, and AVW shortened the DLE by 391 ms on average. MP and AMP gave rise to significantly larger effects than did 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 (toward 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 with the control condition (Figure 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 from one 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 did the other three devices (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 (toward 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: $p < .05$).

Steering Reaction Time

Statistics showed a significant effect of all driving assistance devices on steering reaction times compared with the control condition. This was observed both in bends (mean observed effect [d] = 93 ms, $\delta > 72$ ms), $t(15) = 6.06$, $p < .001$ (Figure 5), and in straight lines ($d = 164$ ms, $\delta > 144$ ms), $t(15) = 10.98$, $p < .001$ (Figure 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 was found ($d = 63$ ms, $\delta > 50$ ms), $F(4, 60) = 5.52$, $p < .002$, but post hoc analysis revealed that only VW and AMP significantly differed from each other ($p = .04$). On average, the side of lane departure did not significantly influence the effects of assistance devices on

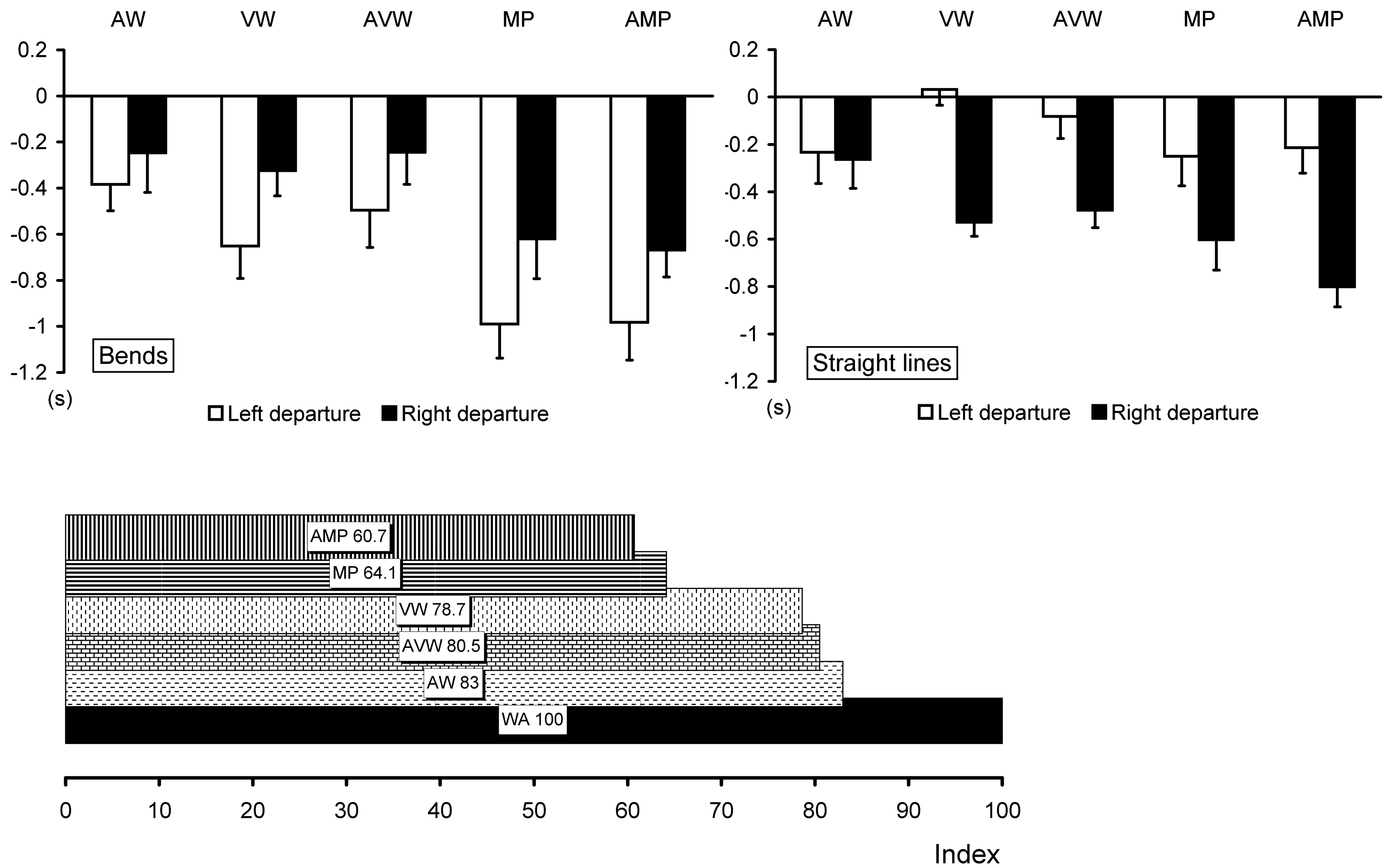

Figure 4. Top panels: Effects of driving assistance devices on the duration of lateral excursion relative to the control condition (WA). WA average = 1.97 s in bends and 1.39 s in straight lines. Error bars represent one standard error. Bottom panel: Proportional duration of lateral excursion for all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

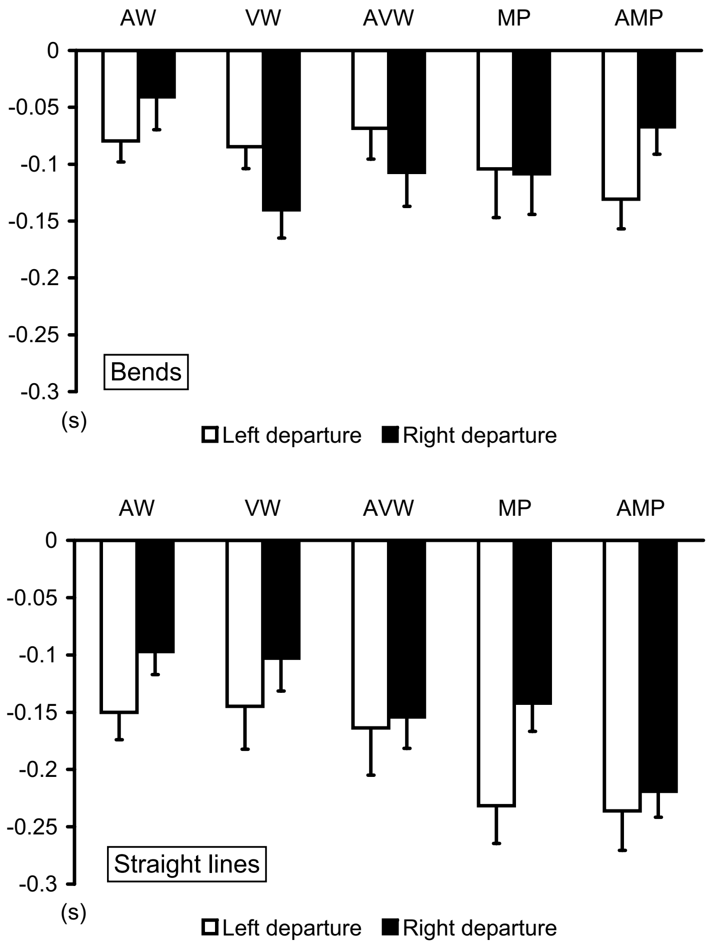

Figure 5. Effects of driving assistance devices on steering reaction times relative to the control condition (WA). WA average = 0.45 s in bends and 0.53 s in straight lines. Error bars represent one standard error.

steering reaction times, either in bends, $t(15) = 0.03$, $p > .97$, or in straight lines, $t(15) = 1.58$, $p > .13$.

Maximum Rate of Steering Wheel Acceleration

Bends and straight lines revealed very similar patterns of results (see Figure 6). Thus, analyses were regrouped. All devices significantly increased the maximum rate of steering wheel acceleration. The ANOVA revealed a significant effect of 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 ($d = 0.7°/s^2$, $\delta > 0.58°/s^2$), $t(15) = 7.76$, $p < .001$. A comparison of MP and AMP found no significant difference. Similarly, VW and AVW did not differ from each other. Once again, MP and AMP gave rise to larger effects than did VW and AVW ($d = 0.57°/s^2$, $\delta > 0.49°/s^2$), $t(15) = 9.99$, $p < .001$.

Overshoot

None of the assistance devices yielded a significantly different overshoot when compared with the control condition, in bends (average decrease of 0.02 m) and in straight lines (average increase of 0.08 m). Moreover, no differences were found among 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

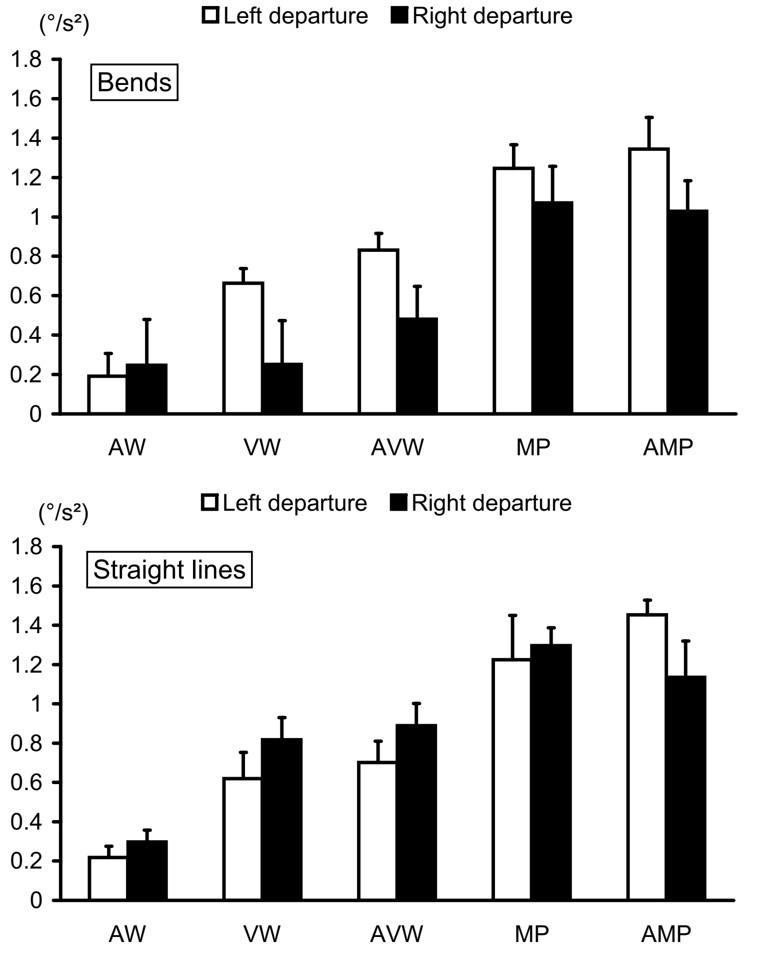

Figure 6. Effects of driving assistance devices on the maximum rate of steering wheel acceleration relative to the control condition (WA). WA average = 1.04°/s^2 in bends and 0.53°/s^2 in straight lines. Error bars represent one standard error.

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 one another 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 among 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 did 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, as overshoots did not differ among driving assistance devices. MP modes did not give rise to unsafe behavior.

It is important to consider that the MP devices performed only minimal corrections to the car's trajectory. As such, they cannot be considered as LKASs. In a situation in which the driver does not hold the steering wheel (or at least holds the wheel very lightly) while slowly drifting toward 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, in which 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 or not information about the direction of lane departure was given. Actually, it was observed that steering wheel corrections were a little sharper with VW (nondirectional 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 vibrotactile 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 nondirectional 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 with unimodal haptic devices, corresponds to the "best of both worlds" pattern described by Wickens and Gosney (2003). Although 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 provided only 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 a 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 attributable to the triangular signal form (Figure 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 in which 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. As with warning devices, drivers were able to take into account elements of the driving context while 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 be seen for only 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, drivers may have estimated the risk to be greater when entering the opposite lane than when going off 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, depending on the context, may have modulated the effects of the assistance device on the corrective maneuver. 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, which 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 in which 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 its installation in actual cars is considered. 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, which 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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