Can drivers modulate the effect of a motor priming assistance device during lane departure?

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Abstract

Traditional Lane Departure Warning Systems are designed to improve the driver's assessment of vehicle position. Motor priming (MP) devices, consisting of fast directional oscillations on the steering wheel, are also hypothesized to directly trigger the corrective motor response. The efficacy of MP has been proven (Navarro et al., 2007, 2010). It remains to determine whether drivers would be able to modulate or inhibit the effects of MP effects when necessary (e.g., weak risk, system failure). In two simulator studies, the effect of two levels of MP strength was studied in lane departure situations. First, we addressed the question of how the effect of MP could be modulated by expected risk. Second, we determined whether an erroneous directional cue could be inhibited and countered. Results showed that MP reduced lane excursion duration, to a greater degree with strong MP than light MP. The lower the expected risk, the higher was the duration of excursion, whatever the strength of the motor cue. Drivers inhibited their steering response and countered MP when its direction was erroneous. In some cases, due to shorter reaction times, the duration of lateral excursions was reduced even with the invalid cue. Thus, MP improved recovery manoeuvres, whilst drivers remained in full control of steering. This suggests a modulation of the effect of MP by higher levels of cognitive control.

Introduction

According to Najm, Smith, and Yanagisawa (2007), in the United States, 66% of accidents involving just one light vehicle are related to road departure. As a solution, driver assistance systems are becoming more and more sophisticated. Various kinds of devices are being developed and these systems can be positioned on a continuum according to their degree of intervention (Hoc, Young, & Blosseville, 2009). For example, lane departure warning systems (LDWS) are created to improve drivers' alertness when a situation becomes dangerous. By way of contrast, lane keeping systems (LKS) share control of the vehicle with drivers (Griffiths & Gillespie, 2005). These are aimed at improving on simple warning systems with only minimal intervention on the steering wheel; such a system, called "motor priming" (MP), has been designed by Navarro, Mars, and Hoc (2007). MP triggers small asymmetric oscillations on the steering wheel when the car is about to cross one of the lane edge lines. The first movement of the steering wheel and every second movement are

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directed toward the road centre, with a stronger torque and speed than those directed towards the side of lane departure. The aim is to deliver directional information to the steering wheel without correcting the trajectory of the vehicle. In this way, the device intervenes at the motor level, proprioceptively pre-activating the corrective gesture, without actually performing it in place of the driver.

The current study follows on from work carried out by Navarro, Mars and Hoc (2007) and Navarro, Mars, Forzy, El-Jaafari, and Hoc (2010). These studies aimed at assessing several lateral control assistances devices. The main results showed that MP was more effective than all other types of audio or vibratory warning, including directional ones. The benefits of all assistance devices were measured during lane departures, which were generated by visual occlusion or driver distraction at specific locations. All driving assistance devices improved recovery manoeuvres in comparison with a condition without assistance, with drivers spending less time in a dangerous lateral position. However, the benefits were significantly greater with the MP device. This was due to an improved action on the steering wheel once the corrective manoeuvre was initiated. The results gathered by Navarro et al. (2007, 2010) support the idea that MP not only improves situation diagnosis, in the same way as warning systems, but also provides a motor cue to the effectors of steering control, i.e. the hands.

Studying a device that acts in a way that is similar to MP (using a directional pulse on the steering wheel), Suzuki and Jansson (2003) found that some drivers turned the steering wheel in the wrong direction. The production of those erroneous responses could be explained, in part at least, by the lack of explanation given to the participants. Alternatively, this could demonstrate that directional pulse can act directly at a motor level insofar as some drivers turned the steering wheel without considering the driving context. Following this reasoning, Kullack, Ehrenpfordt, Lemmer and Eggert (2008) proposed a device, called ReflektAS, which operates in the opposite way to MP. The philosophy was to elicit a reflexive reaction by means of a jerk of the steering wheel in the direction of lane departure. Their idea was that the jerk would yield a stereotyped and automatic response in the opposite direction, which could not be inhibited, with very short response times. As such, the ReflektAS principle is quite different from MP. Both systems are supposed to act at the sensori-motor level to elicit improved motor response. However, whilst MP aims at initiating the arm movement through proprioceptive priming, ReflektAS taps into more basic neural circuitry and inhibition becomes impossible by definition. This leads us to examine with the utmost care the question of drivers’ ability to control the effects of such devices and to stay in control of their vehicles. Prochazka, Clarac, Loeb, Rothwell, and Wolpaw (2000) addressed the ancient debate of reflex versus voluntary movements in the light of recent advances in the field of neuroscience. The conclusion is that, when consciousness is brought into the debate, a movement is considered as voluntary if it can be modulated or inhibited. So, in terms of ergonomics, the question becomes one of whether drivers can modulate or inhibit the effects of MP.

It is acknowledged that driving is a dynamic situation in which different levels of control interact (Michon, 1985). The model of cognitive control proposed by Hoc and Amalberti (2007), which emphasizes the roles and interrelations of four main control modes, is a good choice for interpreting levels of intervention of MP. The symbolic control is close to the conscious or controlled processes and the subsymbolic control can be understood like something more automated, close to the sensori-motor control loops. In this model, two dimensions are crossed - symbolic vs. subsymbolic control, and external vs. internal control. The level of abstraction of the data required for control (symbolic vs. subsymbolic) is very close to the Skill-Rule-Knowledge model introduced by Rasmussen (1986), and can be understood as a continuum between two opposite levels of control. Hoc and Amalberti (2007) underline the role of (symbolic) supervision, which calibrates the execution of (subsymbolic) routines, modelled by Anderson et al. (2004). Within the framework of this model, MP can be understood as a first action (motor priming) at a subsymbolic level, which is then validated by situation diagnosis. Hence, even though MP acts at the subsymbolic level, the driver can choose to perform the primed response or even stop its execution. ReflektAS can also be interpreted within this framework (Kullack et al., 2008) as a deeper (lower) intervention of the system on the continuum between symbolic and subsymbolic processes.

The present study aims to explore the specific continuum of symbolic and subsymbolic processes by integrating supervision processes in driving situations where the MP device intervenes. Two hypotheses are made. First, the symbolic processing of the context will lead to the modulation of the influence of MP on the subsymbolic process. Second, the supervision of routines will lead drivers to inhibit or modulate the effects of MP, at least in part, when the system provides an inadequate incentive.

Method

Participants

Four women and fourteen men, 27 years of age on average (from 20 to 61 years old, *SD* = 11) volunteered to take part in this experiment. Driving experience ranged from 2 to 27 (8.6 years on the average). None of them had ever used lateral control assistance devices.

Equipment

The study took place in a fixed-base driving simulator. This consists of a single-seat cockpit with full instrumentation. It is equipped with an active steering system for a realistic “scale one” force-feedback. The SCANNeRII[•] software package was used with the CALLAS© dynamic vehicle model (Lechner et al., 1997). The visual environment was displayed on three 32-inch LCD monitors, one in front of the driver and two laterals inclined of 45° from the front one, viewed from a distance of about

[•] http://www.scanersimulation.com

1 meter and covering 115° of visual angle (figure 1). The graphics database reproduced a wide country environment.

Figure 1. IRCCyN driving simulator

Driving assistance system

Three conditions of driving were counterbalanced, one without assistance and two with different strengths of MP. MP was generated by asymmetrical triangular oscillations on the steering wheel during a one-second period (frequency = 3.3 Hz; amplitude in the direction of lane centre = 2N/m for light MP and 6 N/m for strong MP; amplitude in the direction of lane departure = 0.5 N/m for all MP strengths).

Procedure

The experiment consisted of two sessions for all drivers. The first lasted 60 minutes, the second 50 minutes. In the beginning, participants drove 10 minutes in order to become accustomed to the simulator. Participants were instructed to drive in the right lane as they usually would and to respect a speed limit of 70 km/h. The functioning principle of the assistance device was explained. During each session, four complete laps of the test track were performed for each driving condition. Thus, twelve laps were performed for each session. During each lap two occlusions could occur at four different positions. Occlusions consisted of suddenly blackening all screens. When visual occlusion occurred, participants were asked to stop making adjustments to steering. Two occlusions were positioned in bends, one leading to lane departure to the right, the other to the left. The remaining occlusions took place in straight lines, also toward different directions. Visual occlusions that occurred when entering bends caused a natural lane departure toward the outside edge line in left bends and toward the centreline in right bends. In order to standardize the direction of lane departure in straight lines, a slight and imperceptible shift in the vehicle heading was introduced when the visual occlusion occurred. Drivers recovered vision when lane departure was imminent: this is precisely the point when the driving assistance device is put into action. Only two occlusions occurred per lap and were thus relatively unpredictable. Moreover, their orders of occurrence were counterbalanced within subjects.

In the first session
Driving assistance conditions were crossed with two levels of risk expectation. During visual occlusion, either “Minor risk” (in green) or “Warning! Major risk” (in red) was displayed on the screen. In addition, in the major risk situation, traffic cones appeared on the road departure edge in order to confirm the danger. It was hypothesized that the level of risk, manipulated in this way, was processed at the symbolic level by drivers. A modulation of the recovery manoeuvre as a function of the perceived risk level was expected.

In the second session
The three driving assistance conditions were crossed with the appropriateness of MP, in order to study the drivers’ ability to inhibit the effects of MP. In fifty percent of cases, when visual occlusion ended, MP worked properly. In the rest of the trials, the priming signal (stronger pulse) was directed in the direction of lane departure. This will be called erroneous MP from now on.

Within each session, conditions of driving and the appropriateness of MP or risk expectation were fully counterbalanced, the two variables being within-subjects factors.

Data analysis

In order to assess performance, the main dependent variable was the time spent by drivers outside the safety envelope of $\pm$ 80 cm from the lane centre after the end of the visual occlusion (Duration of Lateral Excursion: DLE). The Steering Reaction Time (SRT) corresponded to the time elapsed between the end of the visual occlusion and the time when drivers began to act on the steering wheel. The peak of Steering Wheel Acceleration (SWA) was used to evaluate the strength of the steering reaction. The SWA was computed during the 450 ms following the start of the steering response.

The significance of the effects of all independent variables was assessed for DLE, SRT and SWA by repeated measures ANOVAs. In addition, the population effects sizes were evaluated on the basis of fiducial inference. Within the limited framework of this paper, only part of the analysis will be presented.

Fiducial inference (see Lecoutre & Poitevineau, 2005; Rouanet, 1996; Rouanet & Lecoutre, 1983) is a variant of Bayesian statistical inference, aimed at concluding on the population effect size (δ) on the basis of the observed effect (d), the sample size and variability. It goes beyond the test of significance, which only concludes in terms of the existence of a non-null effect and considers test power. In this paper, we will give the conclusions on effect sizes with a guarantee of .90. For example “δ>20” will mean “the probability for δ being greater than 20 is .90”. This kind of conclusion may be seen as an extension of the confidence interval reasoning, provided that the latter is interpreted in Bayesian terms.

Results

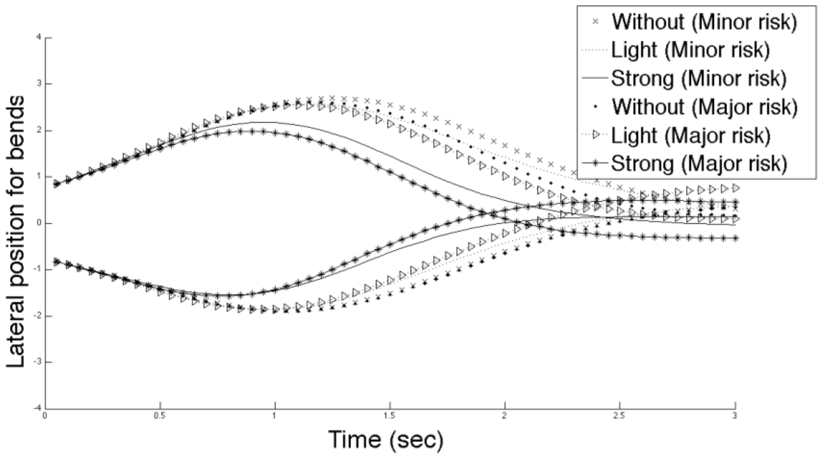

Figure 2. In bends, lateral position of car during the three seconds following the visual occlusion, depending on risk expectation. Top curves represent lane departure on the left and bottom curves on the right. Without: Without assistance; Light: Light; Strong: Strong Assistance

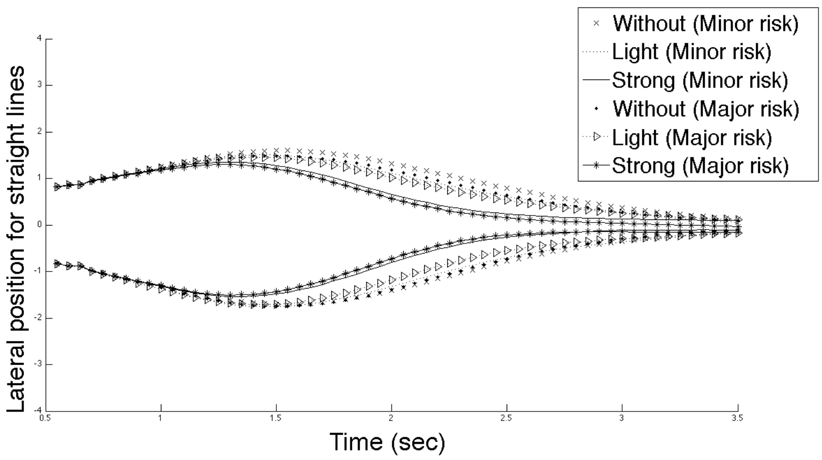

Figure 3. In straights lines, lateral position of car during the three seconds following the visual occlusion, depending on risk expectation. Top curves represent lane departure on the left and bottom curves on the right. Without: Without assistance; Light assistance; Strong: Strong assistance

Figure 2 and figure 3 represent the effect of risk expectation and strength of MP on means trajectories in the first session. These figures revealed that driving with strong

MP and with major risk condition leads to smaller deviation and quicker returns toward the centre of the road, which is positioned on zero on the Y axis. At the opposite, driving without assistance and with minor risk condition leads drivers to higher deviation and longer return toward the road centre. Right bends and left bends revealed very similar patterns of results (Fig. 2). Thus, analyses were regrouped. Similarly, results for bends and straight lines were also qualitatively close (Fig. 3). Due to space limitation, only data for bends will be presented

Duration of Lateral Excursion (DLE)

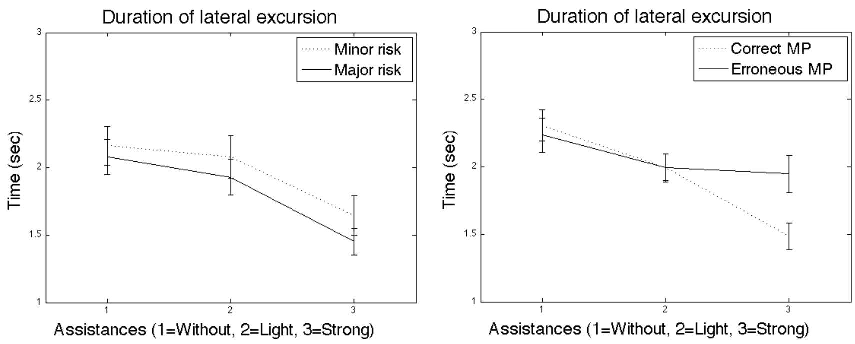

Figure 4. Duration of lateral excursion in bends as a function of risk expectation (left) and appropriateness of MP (right). Without: Without assistance; Light: Light assistance; Strong: Strong assistance

Risk expectation

The ANOVA revealed a significant effect of the driving assistance condition ($F(2, 24)=29.04$, $p<.001$) on the DLE, and no significant interaction between both variables (Fig. 4). Fiducial analysis showed a notable reduction in DLE for strong MP in comparison with the condition without assistance ($\delta>0.44$ sec.). Risk expectation had a significant effect for all driving conditions ($t(12)=3.31$, $p<.01$). In the major risk condition, drivers were quicker to return toward a safe position ($\delta>0.08$ sec.) than in the minor risk condition.

Appropriateness of MP

The ANOVA revealed a significant interaction between driving assistance condition and appropriateness of MP ($F(2, 24)=13.11$, $p<.001$). (Fig. 4). Both light MP systems, erroneous or not, reduced the DLE compared to the control condition ($\delta>0.19$ sec.). For the strong devices, the erroneous one reduced the DLE less ($\delta<0.41$ sec.) than the correct one ($\delta>0.68$ sec.).

Steering reaction time (SRT)

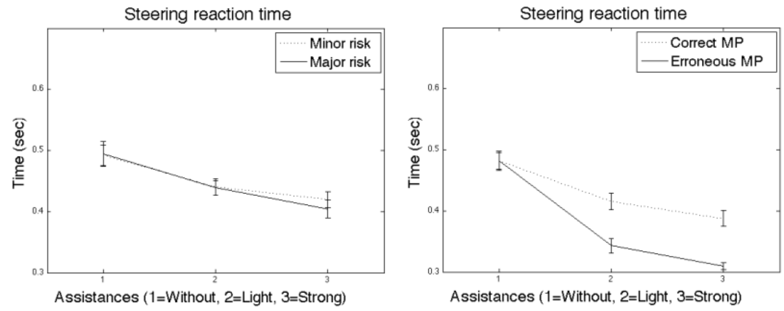

Figure 5. Steering reaction time in bends as a function of risk expectation (left) and appropriateness of MP (right). Without: Without assistance; Light: Light assistance; Strong: Strong assistance

Risk expectation

The ANOVA revealed a significant effect of the driving assistance condition on the SRT ($F(2, 24)=29.41$, $p<.001$), no significant effect of risk expectation, and no significant interaction between factors (Fig. 5). Fiducial analysis showed that the effect of each MP system is notable (strong MP: $\delta > 65$ msec.; light MP: $\delta > 36$ msec.). It also shows that the effect of risk expectation is negligible ($|\delta| < 13$ msec.)

Appropriateness of MP

The data pattern produced by correct MP is very similar to that gathered in the first session (risk expectation); however, erroneous MP did lead to a quicker response than found for correct MP ($\delta > 59$ msec.). The ANOVA revealed a significant interaction between driving assistance condition and appropriateness of MP ($F(2, 24)=13.91$, $p<.001$) and a significant effect of MP devices ($F(2, 24)=142.83$, $p<.001$) (Fig. 5). Fiducial analysis showed that each MP device, erroneous or not, had a notable effect (at least, $\delta > 50$ msec., and at the most, $\delta > 157$ msec.).

Steering wheel acceleration (SWA)

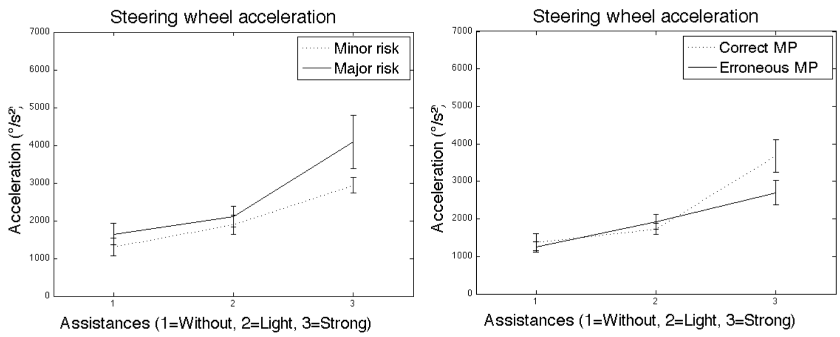

Figure 6. Peak of steering wheel acceleration in bends as a function of risk expectation (left) and appropriateness of MP (right). Without: Without assistance; Light: Light assistance; Strong: Strong assistance

Risk expectation
The ANOVA performed on SWA revealed a significant effect of the driving assistance condition ($F(2, 24)=38.1$, $p<.001$) and an almost non-significant interaction between both factors ($F(2, 24)=1.18$, $p<.19$) (Fig. 6). Fiducial analysis revealed that the two MP devices had a notable effect (light: $\delta > 270°/sec.^2$; strong: $\delta > 1660°/sec.^2$; figures to be compared to an SWA of 2-3000 on the average). In addition, for strong MP, major risk expectation generated much higher SWA than did minor risk ($\delta > 290°/sec.^2$).

Appropriateness of MP
The ANOVA revealed a significant interaction between driving assistance condition and appropriateness of MP ($F(2, 24)=5.51$, $p<.01$) and a significant effect of the driving assistance condition ($F(2, 24)=70.03$, $p<.001$) (Fig. 6). Fiducial analysis revealed that the two MP devices had a notable effect (light: $\delta > 417°/sec.^2$; strong: $\delta > 1605°/sec.^2$). In addition, for strong devices, classic MP generated much higher SWA than did erroneous MP ($\delta > 429°/sec.^2$).

Post-test debriefing

During post-test debriefing, none of the drivers reported that they were aware that MP sometimes ran in an erroneous direction, even with strong MP.

Discussion

This experiment aims to assess whether drivers modulate or inhibit the effects of an MP assistance device depending on risk perception and the appropriateness of the haptic cue relative to the context. Results show that this partly is true A detailed examination of the various steering indicators has enabled us to determine how modulation and inhibition come into play.

Results drawn from the first session show that higher risk expectation significantly reduced the duration of lateral excursion and increased steering wheel acceleration. However, no significant effect was found for steering reaction time. This suggests that steering reaction time essentially depends on subsymbolic processes. However, the effect observed on peaks in steering wheel acceleration, which occurs very soon after the start of the steering response (i.e. circa 500 ms), indicates that the supervision of routines by symbolic processes operates quickly. Drivers were able to take into account elements of the driving context, presented in a very symbolic way (text message and warning cones), to adapt the strength of their corrective manoeuvre to the demands of the situation. Properly speaking, there was no modulation of the assistance effect by risk expectation, but the two factors had additive effects. However, there was modulation of routines (subsymbolic processes) by higher level processes (symbolic processes).

The results observed in the second session, where erroneous MP was studied, complement the previous observations. Whereas risk expectation had previously no significant effect on SRT, it was the case here with erroneous MP. Surprisingly, the fastest responses were observed with erroneous MP. This suggests that when visual occlusion ended, drivers immediately perceived a mismatch between their vision of the vehicle’s motion (heading outside the lane) and the direction of the haptic cue (prompting the hand to steer the vehicle even further in the wrong direction). It can be hypothesized that this sensory mismatch was processed at the subsymbolic level and gave rise to a faster response. However, faster response with erroneous MP did not lead to a larger reduction of the duration of lateral excursion. With MP in the appropriate direction, drivers answered less quickly than with erroneous MP, but performed a more efficient action on the steering wheel. This was especially the case with strong MP, which translated as a larger reduction of DLE in the end. Drivers showed a capability of inhibiting the false directional cue and of turning the steering wheel in the direction appropriate to the (symbolic) analysis of the context.

Several conclusions can be drawn from these observations. First, our results do not fully support the hypothesis proposed by Kullack et al. (2008), according to which a jerk of the steering wheel in the direction of lane departure elicits a more efficient reflexive response in the opposite direction. In both experimental sessions, MP directed towards the lane centre always facilitated an appropriate manoeuvre in that direction, including occasions when strong torque was applied on the steering column. When MP was erroneous, drivers did counteract the system with a shorter reaction time, as observed by Kullack et al. (2008). However, such MP did not help the driver as much as correct MP in terms of safety. The shortening of SRT observed with erroneous MP and the ReflektAS system is most probably the consequence of a perceived mismatch between visual and haptic information, processed at the subsymbolic level, rather than a motor reflex elicited by the jerk. Interestingly, during post-test debriefing, none of the drivers reported that they were aware that MP sometimes ran in an erroneous direction, even with strong MP. This is in accordance with the interpretation that the corrective response is initiated at the subsymbolic level, acting too quickly to allow a clear representation of the action of the device and its effects.

The fact that risk evaluation did not influence the reaction time further supports the idea that the initiation of the steering response is produced at a subsymbolic level. However, most of the execution of the consecutive manoeuvre falls, at least partially, under the influence of supervisory processes. Recorded reaction times were roughly between 300 and 500 ms. The SWA was always measured during the 450 ms that follow the recording of steering reaction time. This means that the modulation and inhibition of the action, in other words the supervision of routines, occurred in less than one second in the experimental conditions of this study.

Conclusion

This study confirms that MP improves the execution of corrective manoeuvres in lane departure situations. It also supports the idea that MP superiority to more traditional warning systems resides in an improvement of response execution at the subsymbolic level (Navarro et al., 2007, 2010). Although this has already been suggested by Navarro et al. (2007), here for the first time it is properly proven that MP does not prevent drivers to modulate their response very early in accordance with risk expectation. Furthermore, drivers were able to inhibit the effects of erroneous MP and, more surprisingly, counteract the system very quickly so that no detrimental effects on the trajectory were observed. Thus, drivers seemed to be able to stay in full control of MP, even in case of system failure.

Further research should aim to determine the benefits of a repetitive haptic cue that lasts for a period of one second, as in the present study, compared to a simple jerk of the steering wheel. Generalizing the conclusions to more ecological situations is also an issue. For instance, visual occlusion might be a specific situation that leads to the visuo-haptic mismatch that is hypothesized to be the origin of the SRT decrease observed with erroneous MP.

Finally, the present paper focuses on the MP system. However, the supervision of other types of systems that are designed to blend into the driver's sensorimotor control loop may pose very similar issues. This is particularly the case with automation based on shared control of the steering wheel (Griffiths & Gillespie, 2005). Also, a clear representation of short- and long-term adaptation of cognitive control to these devices is mandatory.

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