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Driver adaptation to haptic shared control of the steering wheel

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Abstract—**Although the benefits of haptic shared control of the steering wheel have been repeatedly demonstrated, longitudinal studies of how drivers adapt to this kind of system are still lacking. The present study addressed this question by comparing two groups of participants in a driving simulator for an extended time period; one group drove with a shared control system and the other drove without. After the practice, all participants drove a final trial with shared control during which a failure of the system occurred. The results show that the evolution of driving performance and the way in which drivers monitored their performance was similar for the two groups. This suggests that the drivers quickly updated their internal model of the steering system dynamics at the sensorimotor level, without further behavioural adaptation afterwards. However, it appears that the internal model was consolidated with repeated use of the system, which translated as a difficulty to compensate for the system's failure. In addition, it appears that drivers did not attempt to maintain a level of task difficulty when steering was facilitated.**

Keywords—haptic shared control, steering behavior, motor learning, behavioral adaptation, human factors

I. INTRODUCTION

One possible solution for assisting drivers in their control of a vehicle's trajectory is haptic shared control (SC) of the steering wheel, a system that has recently been subject to a great deal of interest [1]–[3]. Such a system applies to the steering system part of the torque that is necessary to follow the road. This action influences the vehicle's lateral position and, at the same time, provides continuous haptic guidance to the driver, who remains in the control loop. The advantages of shared control over manual control in terms of lane-keeping performance, reaction times, comfort and workload associated with a secondary task have been demonstrated repeatedly [4]–[7]. However, longitudinal studies of how drivers adapt to SC systems are still lacking. This study investigated how drivers adapt their steering behavior when sharing control of the steering wheel over an extended time period. In the following paragraphs we will consider the different forms that adaptation may take.

A. Motor learning and consolidation

Current theories of motor control postulate that the control of skilled action requires the building and updating of internal models of the dynamic properties of our own body and the objects with which we interact [8]. When confronted with a new tool, a new internal model of the controlled system must be built (structural learning) or, if a similar tool has already been used, an existing internal model must be updated (parametric learning) [9]. Structural and parametric learning are reminiscent of the classical Piagetian concept of accommodation and assimilation, respectively [10]. It has been demonstrated that drivers can adapt very quickly to a modification of the steering force feedback law. This is the case even when the modification is substantial, such as when force feedback changes from a linear to a non-linear function [11]. Adaptation fails to occur only when there are extreme changes, such as an inverted torque function or a total absence of feedback. Otherwise, adaptation occurs quickly, easily and most often unconsciously. Thus, adaptation to a modification of the steering wheel dynamics seems to be achieved through parametric updating of an internal model of steering wheel compliance. Haptic SC may yield this kind of adaptation. However, as haptic guidance may be less predictable than a simple modification of force feedback rendering, it remains to be determined whether a more substantial (structural) adaptation of the steering wheel control can arise.

When human beings are repeatedly confronted with an external force that modifies the relationship between the motor command and the resulting movement, motor adaptation occurs. Moreover, when the external force is withdrawn, an error is observed in the opposite direction to the initial adaptation [12]–[15]. This after-effect is a typical marker of the updating of an internal model. Consequently, any adaptation to a SC system through the updating of an internal model of the steering wheel dynamics should result in an after-effect. This may be the case when a system failure occurs, for instance. However, this effect may need prolonged experience of the system, even if the initial adaptation to SC was fast. Indeed, recent results suggest that multiple learning processes with different time constants drive motor adaptation [16]–[18]. Fast learning processes respond strongly to errors but have poor retention. When processes with slower dynamics act in parallel, they are less sensitive to errors, but consolidate the motor memory. The combined action of these processes allows fast adaptation to a new tool and also progressive consolidation of the internal model that underpins the use of this tool.

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B. *Modification of cognitive control*

Adaptation to SC can also be considered within the framework of hierarchical models of cognitive control. Rasmussen's SRK (Skills-Rules-Knowledge) model is probably the most well-known [19]. Basically, it considers that a human operator can control a complex dynamic task such as driving on three different levels. Knowledge-based control is in charge of strategic planning (ex: navigation), rule-based control is in charge of tactical decision making (ex: application of explicit or implicit safety rules), and skill-based control governs the operation of the vehicle. Alternatively, these different levels of control may be considered as a continuum between symbolic and subsymbolic processes [20]. Whatever the case may be, cognitive control models consider that the development of expertise in a task relies on the progressive transition of the control of activity from higher cognitive processes to sensorimotor skills. In other words, when learning to adapt to a new situation or to interact with a new system, an operator will first rely on symbolic processes to monitor the activity. Then, he will progressively shift to a routine-based type of control, which will, for example, free cognitive resources for secondary tasks. In the present experiment, we investigated whether this transition is the same when driving with and without SC. If the system blends into the sensorimotor loops, this should be the case. Conversely, the driver may want to keep monitoring the system's influence on steering for a longer period of time.

C. *Global behavioral adaptation*

Finally, the introduction of a SC system in a vehicle may give rise to what is commonly referred to as behavioral adaptation. This term describes changes in behavior that follow on consecutively from the introduction of a new system. These changes were not anticipated by the designer and have the effect of diminishing the expected benefits of the system. For instance, drivers of vehicles with ABS tend to adopt shorter time headway than drivers without ABS [21]. In this case, the adaptation directly concerns the assisted subtask, i.e., longitudinal control. It has also been demonstrated that adaptation can be more global; for example, when adaptive cruise control affects not only longitudinal control but also lateral positioning on a two-lane highway [22]. For safety systems, negative behavioral adaptation can be interpreted as risk compensation. For SC systems, aimed at facilitating steering as much as making it safe, this may be more a matter of task difficulty homeostasis [23]. According to this model, the driver could drive faster to compensate for the decrease in difficulty in the control of lateral position.

D. *Aim of the study*

The present experiment was designed with the previous considerations in mind. Two groups of participants were compared during two sessions in which they drove repeatedly on a track. One group drove with a SC system and the other without it. The evolution of lateral positioning over time was analyzed to determine whether SC influenced the building of expertise, which increased through a better knowledge of the track and better handling of the simulator. The hypothesis was that if adaptation to SC was simply made through the updating of an internal model of the steering wheel dynamics, both groups of drivers should show similar learning curves. We also assessed whether the facilitation of steering induced an increase in speed, even though the system did not physically affect longitudinal control (global behavioral adaptation). In addition, the amount of mind wandering was also measured as an indicator of whether the drivers continued to devote attentional resources to monitoring the driving task with and without SC. In a final trial, an unexpected failure of the system was simulated to evaluate whether the updating of the internal model of the steering wheel was consolidated with driving experience.

II. METHODS

A. *Participants*

Twenty-four participants (3 women and 21 men), ranging in age from 20 to 65 years of age (31 years on average), took part in the experiment. All were licensed drivers with three or more years of driving experience (12 years on average). Self-reported annual mileage for the past year ranged from 1,000 to 30,000 km (mean = 12,270 km). None of them were familiar with lane-keeping assistance systems.

B. *Experimental setup*

The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with full instrumentation (Fig. 1). It was equipped with a Stirling Dynamics/TRW Conekt active steering system for realistic "scale one" force-feedback. The SCANeRII software package was used with the CALLAS dynamic vehicle model [24]. The visual environment was displayed on three 32-inch LCD monitors, one in front of the driver and two lateral ones turned at a 45° angle from the front one, viewed from a distance of about 1 meter and covering 115° of visual angle in width and 25° in height. The graphic database reproduced a country environment. It was a closed track of 4.3 km with bends of various length and curvature. The speed limit was 90 km/h. Traffic in the opposite lane was simulated in order to encourage drivers to stay in their lane. The traffic consisted of 4 cars per minute. Since there was no traffic in the driver's lane, no overtaking occurred. The data acquired by the simulator was recorded at 20 Hz.

Fig. 1. The IRCCyN driving simulator

The SC system was based on the optimal preview control law described in [25]. This control law is based on an H2 optimization algorithm with a preview of the road curvature, which minimizes a weighted sum of lateral deviation from the centerline, heading angle and lateral acceleration. Moreover, the steering wheel torque was limited to 5 Nm, with a maximum variation of 3 Nm/s. Haptic guidance was obtained by applying torque to the steering wheel that was equal to 11% of the torque necessary to keep the vehicle in the middle of the lane. In a previous study, this system setting was demonstrated to give rise to the best human-machine cooperation, with significant gains in terms of lateral control stability, steering effort, comfort and feeling of control [4].

C. Procedure

In order to avoid tiredness among the participants, the experiment was divided into two sessions, which took place over two different days of the same week. In the first session, participants first familiarized themselves with the simulator without SC and then performed six laps of a closed track. The first session lasted approximately one and a half hours. On the second day, the participants drove six more practice laps. The participants were randomly divided into two experimental groups: half of the participants drove with SC, whilst the other half drove without SC. At the end of the second session, the participants in both groups performed one last trial with SC activated. The participants were unaware that the assistance system was inactivated near the end of the track, on a straight section of road just before entering a bend.

D. Data analysis

The evolution of driving performance throughout the practice period was assessed by means of the standard deviation of lateral position and average speed.

Every two laps, each driver was asked to evaluate the time he or she had spent thinking about something else other than driving. A continuous scale of 10 cm was used. This self-reported measurement of mind wandering was considered as an indicator of how much time drivers spent monitoring driving rather than relying only on sensorimotor skills.

In the last trial, the maximum lateral deviation from the centerline was measured in the bend immediately following the system failure.

The evolution of driving performance and mind wandering was tested by means of repeated measures ANOVAs with type of practice (with or without SC) as a between-subject factor. Pairwise comparisons in the familiarization period and the failure scenario were performed using t-tests. The significance threshold was set at p=.05.

III. RESULTS

The data from the familiarization period showed no significant difference between the two groups. The observed differences were 4.96 cm for the variability of the lateral position (t_{12} = 1.04, ns) and 1.25 m/s for the mean speed (t_{12} = 0.45, ns). Hence, the two groups could be considered as equivalent.

Figure 2 represents the evolution of the variability of the lateral position and mean speed for both groups during the 12 laps of driving practice. Statistical analyses revealed a significant reduction in lateral position variability when driving with SC (F(1,22) = 6.26, p<.05). The variability diminished with time (F(11,242) = 4.76, p<.001). However, the interaction between the repetition and the type of practice was not significant (F(11,242) = 1.03, ns). In other words, the improvement of lateral control performance due to the repetition of the task was similar with and without SC.

The analysis of the mean speed data showed that the mean speed with SC was 2.2 m/s lower than the mean speed without SC; however, the difference was not significant (F(1,22) = 1.35, ns). Speed increased with time (F(11,242) = 3.22, p<.001). The interaction between the repetition and the type of practice was not significant (F(11,242) = 0.68, ns), which confirms that the evolution of performance as a function of experience was similar in both cases.

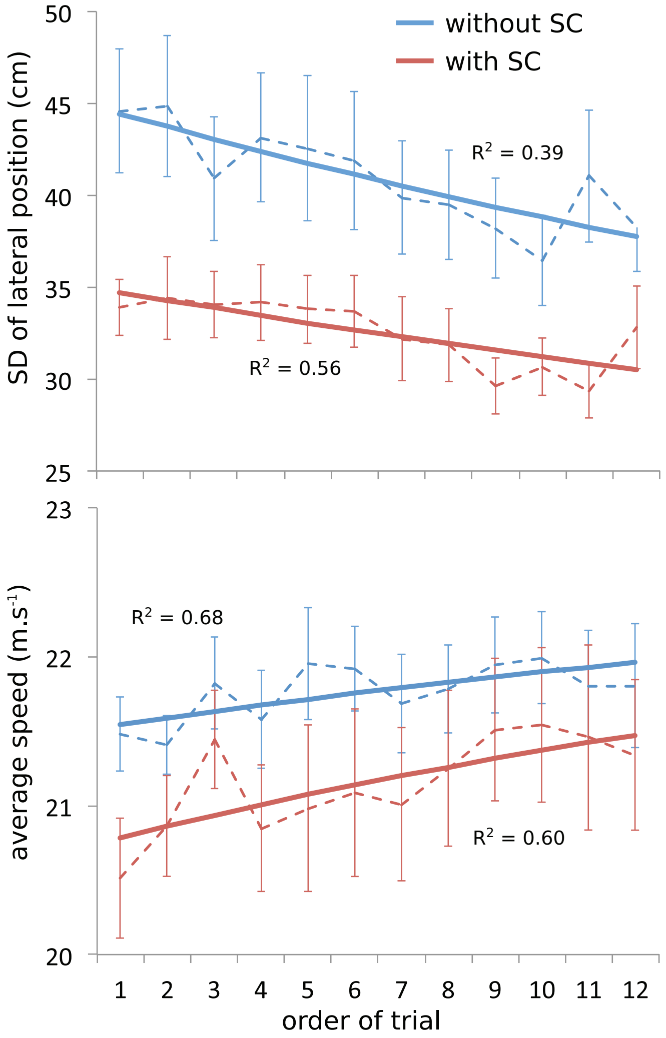

Fig. 2. Evolution of lateral position variability (top) and speed (below) as a function of practice with and without shared control. Dotted lines represent observations, whereas continuous lines represent linear regressions. Coefficient of determination R^2 are indicated. Error bars represent S.E.M.

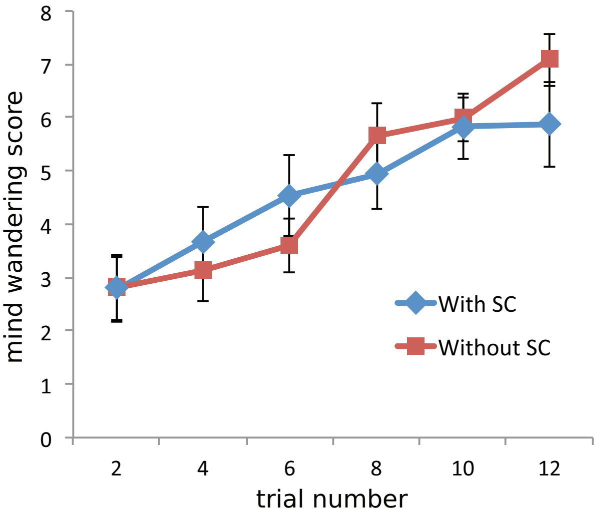

Fig. 3. Evolution of mind wandering as a function of practice with and without shared control. Error bars represent S.E.M.

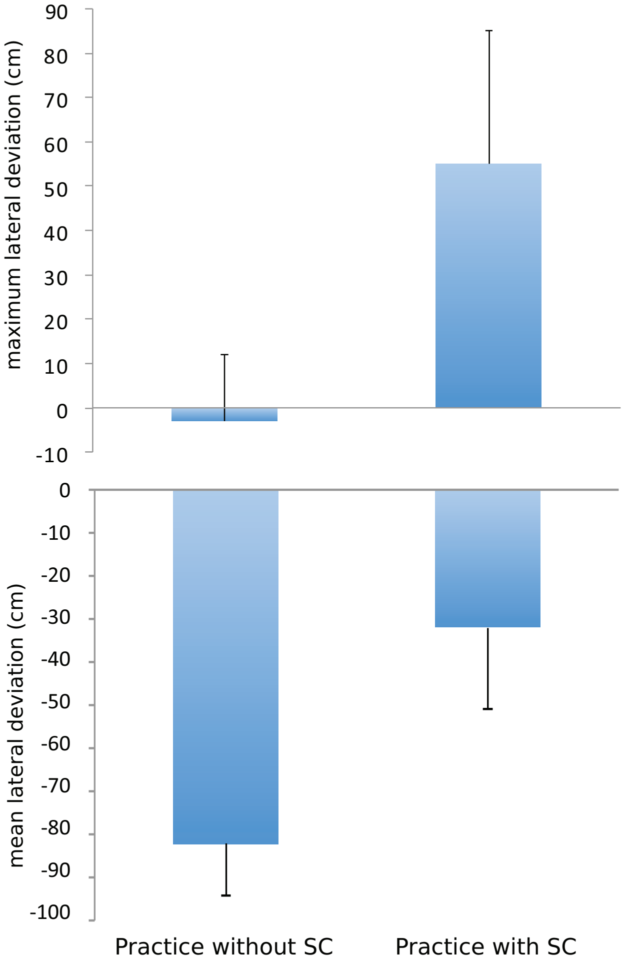

Fig. 4. Maximum (top) and mean (bottom) lateral deviation after failure of the shared control system in the last trial as a function of previous driving practice with shared control. A positive value corresponds to a deviation in the direction of the outside edge line. Error bars represent S.E.M.

Figure 3 shows that drivers reported spending less and less time thinking about the driving task as experience grew. The amount of mind wandering did not significantly differ between the two groups ($F(1,22) = 0.57$, ns). Mind wandering increased with time ($F(5,110) = 12.37$, $p<.001$). The interaction between both factors was not significant ($F(5,110) = 0.89$, ns).

Finally, as shown, the participants who practiced without SC cut the corner in the bend that followed the simulated system failure; their mean lateral position deviated by 82 cm in the direction of the inside edge line (Fig. 4, bottom), which is comparable to what was observed during the practice trials for the two groups (88 cm without SC; 96 cm with SC). This corner-cutting behavior was markedly reduced in the failure trial for the participants who practiced with SC (32 cm; t_{22} =-2.23, $p<.05$). In addition, this group made a maximum lateral excursion of 53 cm in the direction of the outside lane border, on average (Fig. 4, top). By contrast, most of the participants who practiced without SC never or barely crossed the centerline. However, the difference between groups for the maximum lateral deviation was not statistically significant (t_{22} =1.76, p=.09). Since the system failure did not appear in a bend but in the preceding straight line, it did not yield a sudden change in the trajectory. Instead, the mean and maximum lateral deviation data reflect the fact that the drivers veered wide on the bend.

IV. DISCUSSION

This study investigated how drivers adapt to a haptic SC system over time. Results show that haptic shared control immediately reduced lateral position variability when compared with unassisted driving. Comparable results with the same system settings have been reported previously [4]. From the first trial onwards, lateral position variability linearly decreased with practice in a similar way, both with and without haptic shared control. Moreover, drivers progressively disengaged from monitoring their driving, as suggested by the self-evaluation of the amount of time spent mind wandering. This effect was also very similar with and without the activation of SC.

Hence, with the exception of an immediate improvement in lane-keeping performance observed for the drivers who used the SC system, the evolution of driving performance and how drivers monitored this performance was similar for both groups of drivers. This suggests that haptic guidance was seamlessly integrated into the drivers' sensorimotor control loop. This was presumably achieved by a fast parametric adaptation of the internal model of the steering system dynamics, without any other noticeable change in steering behavior afterwards.

However, it appears that the updated internal model was consolidated with repeated use of the system. This translated as a difficulty in compensating for the system's failure, with a lateral excursion in the direction of the outside edge line. By contrast, drivers who only had a few minutes' experience of the system managed to negotiate the critical bend without any problems. This kind of after-effect is a typical marker of sensorimotor adaptation [14]. Our results support the existence of multiple learning processes with differing sensitivity to error and different rates of information retention. [16]–[18]. In the case of driving with SC, a fast learning process with poor retention allowed a quick adaptation to the additional torque provided by the system. On the other hand, a slower process consolidated this motor adaptation, hence creating the conditions for the appearance of the after-effect. In a way, this result underlines how easily SC systems can blend into the sensorimotor loops, with potential benefits both in terms of comfort and safety. It also highlights the necessity to make these systems as reliable as possible because unexpected system failure may yield inappropriate steering behavior.

The results did not show any evidence of global behavioral adaptation. The increase in speed with practice was not larger when the system was active, which suggests that drivers did not attempt to maintain a level of task difficulty when steering was facilitated. Other studies failed to demonstrate this kind of negative adaptation with lane-keeping assistance systems [26]. This is in contrast with well-known risk compensation effects associated with ABS or ACC, both of which act on longitudinal control [21], [22]. This may be because drivers monitor lateral control more cautiously than they do longitudinal control. However, it should be noted that global behavioral adaptation to SC might necessitate several days or weeks, which is more than the couple of hours of driving our participants experienced.

In conclusion, it appears that the adaption to SC was performed at the sensorimotor level through the parametric updating and consolidation of the internal model of the steering wheel dynamics. The system we used has previously been proven to yield good human-machine cooperation [4]. Among the system settings investigated in [4], the one used here provides comparatively low haptic authority, as defined by [2]. To achieve a higher level of haptic authority without negative interference between human and machine, it has been proposed to integrate a driver model within the design of the control law [27]–[29]. In this case, the weighting of the automaton in the human-machine system may be higher, which may give rise to different adaptation processes. These processes remain to be determined with further longitudinal studies.

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