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Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies

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ABSTRACT

An important issue in road traffic safety is that drivers show adverse behavioral adaptation (BA) to driver assistance systems. Haptic steering guidance is an upcoming assistance system which facilitates lane-keeping performance while keeping drivers in the loop, and which may be particularly prone to BA. Thus far, experiments on haptic steering guidance have measured driver performance while the vehicle speed was kept constant. The aim of the present driving simulator study was to examine whether haptic steering guidance causes BA in the form of speeding, and to evaluate two types of haptic steering guidance designed not to suffer from BA. Twenty-four participants drove a 1.8 m wide car for 13.9 km on a curved road, with cones demarcating a single 2.2 m narrow lane. Participants completed four conditions in a counterbalanced design: no guidance (Manual), continuous haptic guidance (Cont), continuous guidance that linearly reduced feedback gains from full guidance at 125 km/h towards manual control at 130 km/h and above (ContRF), and haptic guidance provided only when the predicted lateral position was outside a lateral bandwidth (Band). Participants were familiarized with each condition prior to the experimental runs and were instructed to drive as they normally would while minimizing the number of cone hits. Compared to Manual, the Cont condition yielded a significantly higher driving speed (on average by 7 km/h), whereas ContRF and Band did not. All three guidance conditions yielded better lane-keeping performance than Manual, whereas Cont and ContRF yielded lower self-reported workload than Manual. In conclusion, continuous steering guidance entices drivers to increase their speed, thereby diminishing its potential safety benefits. It is possible to prevent BA while retaining safety benefits by making a design adjustment either in lateral (Band) or in longitudinal (ContRF) direction.

1. Introduction

Advanced Driver Assistance Systems (ADAS) support drivers in tasks such as lane keeping, car following, braking, and obstacle avoidance (e.g., Eichelberger and McCartt, 2016; Ferguson et al., 2008). Generally, ADAS are developed with the goal to increase comfort and safety, and numerous simulator-based and test-track studies have indeed shown such benefits (Bengler et al., 2014; Piao and McDonald, 2008). In reality, however, the anticipated safety benefits are often diminished because drivers show behavioral adaptation (BA), such as driving with a higher speed, driving closer to a lead vehicle, performing distractive non-driving tasks, or driving longer trips as compared to driving without ADAS (Elvik, 2013; Hiraoka et al., 2010; Martens and Jenssen, 2012; Mehler et al., 2014; OECD, 1990; Saad, 2006).

The ability to adapt is intrinsic to humans, and although adaptation can have positive effects in certain circumstances (e.g., close following may be beneficial in terms of highway capacity), most transportation researchers are concerned with adaptations that degrade the safety benefits that can be achieved with ADAS. For example, Sagberg et al. (1996) observed a reduced time headway among taxis equipped with an Anti-lock Braking System (ABS), compared to taxis without ABS. Their results suggest that the taxi drivers exploited the fact that ABS reduces the braking distance by driving closer to the vehicle in front. Such BA with negative consequences has been implicated in many types of ADAS including not only ABS, but also adaptive cruise control (Panou et al., 2007), lane departure warning systems (Rudin-Brown and Noy, 2002), and collision avoidance systems (Janssen and Nilsson, 1993).

The psychological mechanisms behind BA are yet to be elucidated, but it has been postulated that drivers exhibit a trade-off between two conflicting motivations, namely arriving at a destination in time (efficiency) versus avoiding dangerous situations (safety), and whereby the driver's level of subjective risk (Näätänen

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and Summala, 1974; Wilde, 2013, 1998), task difficulty (Fuller, 2005), or time/safety margins (Gibson and Crooks, 1938; Van Winsum et al., 1999) are important homeostatic variables. Accordingly, drivers adopt a higher speed or a shorter headway when the driving task becomes easier, less risky, or less temporally demanding due to a change in the road-vehicle-driver system, such as improved environmental conditions (e.g., when adding road lighting; Assum et al., 1999) or increased assistance in the car driving task (e.g., when using adaptive cruise control; Dragutinovic et al., 2005).

The magnitude of the BA effect is thought to depend on the time driven with the ADAS, the driver's attitude towards the ADAS (e.g., whether the driver uses the system to drive to the limit), driver experience, and the design of ADAS (Carsten et al., 2012; Saad et al., 2004; Sullivan et al., 2016). One supposedly important predictor of BA is the 'noticeability' of the ADAS: It has been said that ADAS which cause directly noticeable differences in the road-vehicle-driver system suffer from BA to a greater extent than ADAS that do not (Elvik et al., 2004a,b). That is, if drivers are more aware that ADAS interferes with their driving task, it is more likely that they will adapt their behavior. For example, larger BA effects have been demonstrated for driving with a night vision enhancement system than for a non-visible feature such as electronic stability control (e.g., Hiraoka et al., 2010; Jiménez et al., 2008). Based on these findings it is expected that ADAS that continuously interact with the driver are more likely to suffer from BA than for instance emergency systems.

One type of ADAS that is growing in popularity and which may be particularly prone to BA is haptic steering guidance. The philosophy of haptic steering guidance is to use the control interface as a medium of cooperation between the driver and an intelligent vehicle, with the aim to keep the driver informed and involved in the driving task, and to prevent the out-of-the-loop problems that occur in hands-free automated driving (Abbink et al., 2012; Flemisch et al., 2008; Griffiths and Gillespie, 2005; Johns et al., 2016; Mars et al., 2014a; O'Malley et al., 2006; Soualmi et al., 2014, see Petermeijer et al., 2015b for a review). Concretely, haptic steering guidance continuously assists drivers in the steering task by providing torques on the steering wheel based on the target steering behavior of an automated controller. The driver may 'relax' his muscles and conform to the applied torque, or may steer against it. Thus, the human and the machine are jointly steering the car, and the degree of support can vary along a continuous scale from driver-in-control (i.e., the driver has a firm grip on the steering wheel and overrides the applied torques) to machine-in-control (i.e., the driver has a very light grip on the steering wheel). Previous research has shown beneficial effects in terms of improved lane-keeping performance, increased safety margins, and reduced self-reported workload for driving with steering guidance as compared to unsupported driving (Mars et al., 2014b; Mulder et al., 2012; O'Malley et al., 2006). In summary, due to the continuous interaction, increased controllability, and reduced workload, haptic steering guidance may be highly susceptible to BA.

Recently, researchers have started to investigate the hypothesis that the beneficial effects of haptic guidance might be accompanied by unintended side effects. A driving simulator study by Petermeijer et al. (2015a) found that drivers showed dangerous steering oscillations, also called 'aftereffects', after the steering guidance failed prior to entering a curve. As with most research on haptic steering guidance (e.g., Griffiths and Gillespie, 2005; Mohellebi et al., 2009; Mulder et al., 2012), the vehicle speed in this study was held constant. It is yet unknown whether participants driving with haptic steering guidance will show BA in terms of increased driving speed when the guidance system is active and functioning normally. The only study on this topic found no BA with continuous haptic steering guidance compared to manual driving (Mars et al., 2014b). The authors compared two groups of participants in a driving simulator; one group drove with haptic steering guidance and the other drove without. No statistically significant speed difference was found between the two groups; however, due to the between-subject design, this particular study may have lacked the statistical power to detect a difference in mean driving speed.

The aim of the present research was twofold. As indicated above, haptic steering guidance is a noticeable type of ADAS and may therefore be highly susceptible to BA. Our first aim was to test the hypothesis that haptic steering guidance causes BA operationalized as driving speed. Driving speed is a prime measure of BA with strong implications for road safety (Elvik, 2013): An increase of speed reduces a driver's time to respond in an emergency scenario, increases the probability of being involved in a crash, increases the driver's severity of injury if a crash occurs, and increases the severity of injury of (vulnerable) road users that are hit by the driver (Aarts and Van Schagen, 2006; Elvik et al., 2004a,b; Hedlund, 2000).

Our second aim, anticipating on the hypothesized BA caused by haptic steering guidance, was to investigate the effectiveness of two types of haptic steering guidance that were developed to mitigate speeding without compromising the beneficial effects of guidance on safety and comfort. The first design (Band) incorporates a lateral bandwidth whereby the guidance engages only when the vehicle deviates substantially from the lane center. This design was previously tested at a constant driving speed and was found to mitigate effects of over-reliance in case the system suddenly failed (Petermeijer et al., 2015a). The second design is a longitudinal boundary system (ContRF) that removes the continuous guidance when driving faster than a pre-defined speed threshold. These fundamentally different systems were both hypothesized to reduce speeding: the Band condition is equivalent to driving manually unless making a large lateral error (thereby providing guidance only when needed), and the ContRF condition provides guidance in normal conditions, but ceases to function when the driver adopts a high speed (thereby removing the benefits of guidance when driving fast).

This study evaluated driving behavior when driving with haptic steering guidance systems on a narrow road with cones along the entire road, compared to unsupported driving. Prior to each guidance condition, drivers were familiarized with the working mechanisms of the steering guidance. This was done because a BA effect may appear only after a learning period that allows drivers to develop a mental model of the system (Beggiato et al., 2015; Bianchi Piccinini et al., 2014; Martens and Jenssen, 2012; Saad, 2006; Sullivan et al., 2016). To enhance the familiarization process, each guidance condition was explained to the participants in detail. During the actual experiment, drivers were instructed to drive as they normally would while minimizing the number of cone hits. Drivers received real-time feedback on their lane-keeping performance: a cone hit was indicated by means of a red dot appearing on the screen. The augmented feedback (i.e., red dots) and narrow road were assumed to enhance the subjective risk and noticeability of the lane-keeping benefits of the haptic guidance, and to discourage participants from driving at full speed (see Zhai et al., 2004 for a speed-accuracy trade-off in lane keeping). Due to these factors, it was expected that *if* haptic steering guidance suffers from BA, this effect would be detected sooner. To investigate the potential risks of speeding, a sharp curve was introduced at the end of the trial trajectory.

The aim of this study was to investigate the effect of three different designs of haptic steering guidance on speeding. It was hypothesized that when driving with continuous steering guidance participants would adopt a higher speed than when driving manually without support. Furthermore, a lateral and longitudinal alternative steering guidance were tested. Both designs were