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Are you in the loop? Using gaze dispersion to understand driver visual attention during vehicle automation

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ABSTRACT

This driving simulator study, conducted as part of the EC-funded AdaptIVe project, assessed drivers' visual attention distribution during automation and on approach to a critical event, and examined whether such attention changes following repeated exposure to an impending collision. Measures of drivers' horizontal and vertical gaze dispersion during both conventional and automated (SAE Level 2) driving were compared on approach to such critical events. Using a between-participant design, 60 drivers (15 in each group) experienced automation with one of four screen manipulations: (1) *no manipulation*, (2) *manipulation by light fog*, (3) *manipulation by heavy fog*, and (4) *manipulation by heavy fog with a secondary task*, which were used to induce varying levels of engagement with the driving task. Results showed that, during automation, drivers' horizontal gaze was generally more dispersed than that observed during manual driving. Drivers clearly looked around more when their view of the driving scene was completely blocked by an opaque screen in the *heavy fog* condition. By contrast, horizontal gaze dispersion was (unsurprisingly) more concentrated when drivers performed a visual secondary task, which was overlaid on the opaque screen. However, once the manipulations ceased and an uncertainty alert captured drivers' attention towards an impending incident, a similar gaze pattern was found for all drivers, with no carry-over effects observed after the screen manipulations. Results showed that drivers' understanding of the automated system increased as time progressed, and that scenarios that encourage driver gaze towards the road centre are more likely to increase situation awareness during high levels of automation.

1. Introduction

The past decade has seen a rapid development of vehicles equipped with Advanced Driver Assistance Systems (ADAS), culminating in multiple vehicle manufacturers releasing first-generation automated driving functionalities such as Lane Keeping Assist (LKA) and Adaptive Cruise Control (Level 2, partial automation; SAE, 2014). These include the Volvo XC90 (Volvo Cars, 2015), Tesla Model S (Tesla Motors, 2015), and Infinity Q50 (Infinity, 2015). While vehicle automation promises a number of social and individual benefits, including increased mobility (Rosenbloom, 2012), safety and efficiency (Anderson et al., 2014), it also shifts the driver's role, from that of an active operator to that of a passive supervisor (Merat et al., 2012). Some authors have suggested that this supervisory role takes drivers "out-of-the-loop" (OOTL) and impairs their ability to manage critical situations when performance after automation failure/limitations is compared to manual driving

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(Rudin-Brown and Parker, 2004; Gold et al., 2013; Strand et al., 2014; Merat et al., 2014). While the origin of this OOTL concept is based on the effect of automation on performance within other domains (Wiener and Curry, 1980; Bainbridge, 1983; Norman and Orlady, 1989; Endsley and Kiris, 1995; Rasmussen and Rouse, 2013), the term is not yet currently well-defined when addressing the impact of vehicle automation on driving performance. Yet, from a human factors and road safety perspective, it is important to investigate the nature and consequences of this OOTL state and understand, for example, how it influences drivers' distribution of attention during high levels of automation, or how it affects their ability to resume control from automation in an appropriate and timely manner, should a system limit be reached. This paper, therefore, describes a driving simulator study that attempted to simulate the OOTL concept in vehicle automation and reports on the distribution of drivers' visual attention during SAE level 2 automation as a means of assessing this methodology.

According to Kienle et al. (2009), a driver is considered OOTL when they are "not immediately aware of the vehicle and the road traffic situation because they are not actively monitoring, making decisions or providing input to the driving task". Norman (1990) attributes causality not to automation per se but rather to a lack of continual feedback. The concept seems, therefore, to include two elements; one, which relates to the awareness of elements in the environment, and another, which relates to the awareness of elements regarding vehicle status and its automated system(s).

Seeking to expand on the mechanisms underlying the OOTL problem, Louw et al. (2015a) presented a schematic representation of this concept, which proposes that, as a result of vehicle automation, drivers are removed from a physical control loop, because they are no longer physically interacting with the vehicle's mechanisms such as the steering wheel and pedals (see also Stanton and Young, 1998). Drivers can also be removed from a 'cognitive control loop' and lose situation awareness, either because they are looking away from the driving scene during automation and interacting with a distracting task, or due to boredom/mind-wandering (Lerner et al., 2015). Clearly, both loops are important for contributing to safe driving performance, since, for instance, physical neuromuscular control gives drivers feedback of steering torque and helps contribute to corrections of heading errors (Pick and Cole, 2006), whilst good situation awareness contributes to effective attentional control and decision-making and improves hazard perception, for instance, in response to critical events (Endsley, 2006; Horswill and McKenna, 2004). Accordingly, Louw et al. (2015a) hypothesise that reductions in either or both aspects of control, brought about by automation, can contribute to less effective return-to-manual performance, but that not being in physical control can also act to impair situation awareness, which consequently can reduce driving performance.

To further investigate this concept, the current study sought to induce a range of OOTL states by removing driving-relevant information during automation and explored whether these affected drivers' ability to regain situation awareness in response to a potentially critical event. Based on the Kienle et al. (2009) definition, being in the loop involves three distinct elements: drivers must (i) be aware of the vehicle (ii) be aware of the road traffic situation and (iii) make decisions or provide input to the driving task (when resuming control). We, therefore, designed a study where we examined how drivers' ability to respond to potentially critical situations which followed a system-initiated automation disengagement, was affected by the systematic removal of the three elements mentioned above, thereby inducing an artificial OOTL state. This was achieved by developing a screen manipulation technique, introduced in Louw et al. (2015a) and Louw et al. (2016), which uses a fog-like display to vary the degree of visual information available to drivers during automation, both in terms of the dashboard displays in the vehicle and also the road environment itself (see Fig. 2, and Methods section for a more detailed outline). This approach broadly resembles a visual occlusion technique, first used by Senders et al. (1967) to model driver behaviour based on information theory, and then others to quantify the visual demand of in-vehicle information systems (Foley, 2009).

Extended durations of automated driving have been shown to take drivers further OOTL (Körber et al., 2015). However, here, we were simply interested in assessing whether removing driving-relevant information, with short periods of such screen manipulations, would take drivers OOTL, and what the effects of such manipulations would be on drivers' visual attention. Of course, one simple method for taking drivers OOTL (both physical and cognitive) is to allow interaction with a secondary task during automation. However, our rationale for using screen manipulations was to reduce the complications associated with the physical demand of engaging in a secondary task (Zeeb et al., 2015), which can take drivers' head, hands and eyes away from the driving scene (Carsten et al., 2012; Louw et al., 2015b) and adds considerable individual variability during the return to manual control.

Traditionally, analysis of drivers' performance in the transition period from automation to manual control has relied on the use of vehicle-based metrics and reaction time measures, following a mandatory resumption of control from a failing or limited automation system (Gold et al., 2013; Louw et al., 2015b; Merat and Jamson, 2008). However, while it is relevant to establish the minimum time required for drivers to resume control of the vehicle after automation disengagement (termed a take-over-response or TOR; see Beller et al., 2013; and Helldin et al., 2013), we argue that such instructions to resume control may simply be in response to alarms and experimenter commands, and not a reflection of drivers' recognition of, and ability to manage, an emerging critical situation. This argument is supported by Gold and colleagues' finding that while a relatively rapid resumption of control from automation is possible, where the first braking input can be as fast as 2.06 s, and steering input is around 2.27 s, it is at the cost of safe vehicle control (Gold et al., 2013). Therefore, our aim was to investigate drivers' assessment of the environment following a period of screen manipulation using an uncertainty alert, which declared the automation might not be able to handle the unfolding situation, and investigated how each screen manipulation condition affected drivers' ability to evaluate the criticality of events and decide whether resumption of control was necessary. We also assessed whether repeated exposure to such events influenced drivers' visual attention.

To assess drivers' attention to the driving scene and vehicle controls during, before and after each screen manipulation, we considered their visual attention to different areas of interest, using eye gaze dispersion. Psychophysiological research