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Is take-over time all that matters? The impact of visual-cognitive load on driver take-over quality after conditionally automated driving

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ABSTRACT

Currently, development of conditionally automated driving systems which control both lateral and longitudinal vehicle guidance is attracting a great deal of attention. The driver no longer needs to constantly monitor the roadway, but must still be able to resume vehicle control if necessary. The relaxed attention requirement might encourage engagement in non-driving related secondary tasks, and the resulting effect on driver take-over is unclear.

The aim of this study was to examine how engagement in three different naturalistic secondary tasks (writing an email, reading a news text, watching a video clip) impacted take-over performance. A driving simulator study was conducted and data from a total of 79 participants (mean age 40 years, 35 females) were used to examine response times and take-over quality. Drivers had to resume vehicle control in four different non-critical scenarios while engaging in secondary tasks. A control group did not perform any secondary tasks.

There was no influence of the drivers' engagement in secondary tasks on the time required to return their hands to the steering wheel, and there seemed to be only little if any influence on the time the drivers needed to intervene in vehicle control. Take-over quality, however, deteriorated for distracted drivers, with drivers reading a news text and drivers watching a video deviating on average approximately 8–9 cm more from the lane center. These findings seem to indicate that establishing motor readiness may be carried out almost reflexively, but cognitive processing of the situation is impaired by driver distraction. This, in turn, appears to determine take-over quality. The present findings emphasize the importance to consider both response times and take-over quality for a comprehensive understanding of factors that influence driver take-over.

Furthermore, a training effect in response times was found to be moderated by the drivers' prior experience with driver assistance systems. This shows that besides driver distraction, driver-related factors influencing take-over performance exist.

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1. Introduction

Driver assistance systems are widely used today. Although the first systems were mainly safety systems (e.g., electronic stabilization program, antilock braking system), more advanced systems now not only improve road safety, but also aim to increase driver comfort by taking over (parts of) the driving task. Specifically, increasing effort is put in developing conditionally automated driving systems which take over both longitudinal and lateral vehicle control. According to the definition of conditionally automated systems as given by SAE International (2014), the driver no longer has to constantly monitor the driving environment and is consequently enabled to engage in non-driving related tasks. However, the driver must still be able to take back vehicle control if necessary. It is this aspect that has stimulated research on driver take-over in the last few years.

1.1. Driver take-over

A conditionally automated driving system must be able to detect system boundaries (e.g., missing lane markings, construction sites, heavy weather conditions). If such a system boundary is detected, a take-over request is prompted and the driver has to take over vehicle control within a sufficient (to be defined) time budget. Several perceptual, information processing, and action-based processes during driver take-over have been identified (Gold and Bengler,

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2014; Zlocki and Eckstein, 2014) which appear to proceed partly sequentially and partly in parallel (Zeeb et al., 2015). In the following, these aspects of driver take-over are described for a visually distracted driver.

Subsequent to a take-over request, drivers redirect their gaze from the secondary task to the roadway. If necessary, they will also return their hands to the steering wheel and their feet to the pedals. By doing so, drivers establish motor readiness, allowing them to intervene in vehicle control (Zeeb et al., 2015). Previous studies report reaction times of about 0.7–1 s for the first road fixation, and 1.2–1.8 s for the first contact with the steering wheel (Gold et al., 2013; Zeeb et al., 2015). In case drivers are visually distracted and not looking at the roadway when a take-over request is initiated, the cognitive processing of the take-over situation may start as soon as they shift their visual focus back to the street (Gold and Bengler, 2014; Zeeb et al., 2015). This includes perceiving the situation and updating the current mental model by integrating relevant elements into a coherent model of the situation (Endsley, 1995). Based on the mental model, an action can be selected and executed, resulting in an actual driver intervention in longitudinal or lateral vehicle control by steering, braking or accelerating.

1.2. Factors influencing driver take-over

Take-over time and quality were shown to be influenced by several factors such as involvement in a secondary task (Merat et al., 2012), the complexity and criticality of the driving situation (Merat et al., 2012; Radlmayr et al., 2014), or modality and intensity of the take-over request (Naujoks et al., 2014). Gold et al. (2013) further report that take-over time depended on the given time budget. Drivers showed longer response times when they were given a time budget of 7 s instead of 5 s. While most research conducted to date focused on external factors, there is also evidence for driver-related factors affecting take-over time and quality. The driver's strategy of monitoring the roadway was found to influence take-over performance (Zeeb et al., 2015). Gold and Bengler (2014) report faster and better driver reactions when encountering a take-over situation for the second time compared to the first time. While a behavioral adaptation after the first take-over situation can be expected, it remains unclear how learning effects play out for more than two take-over situations. Furthermore Larsson et al. (2014) found an influence of driver experience with ACC on response times to an unexpected driving event during automated driving. ACC-experienced drivers started braking faster than drivers inexperienced with ACC. However, the authors considered only one situation and point out the necessity to further examine how long it takes inexperienced drivers to adapt their response times. Hence, while there is some evidence for the impact of driver-related factors on the ability to resume vehicle control, some aspects remain unclear and require further research.

It should be assumed that such factors do not necessarily affect all aspects of driver take-over, but might have a selective effect on the single processing steps described above. Zeeb et al. (2015) found that the driver's individual monitoring strategy affects the time before the driver intervenes in vehicle control, but not the time the driver needs for the first glance at the road and for the first contact with the steering wheel. These authors thus assumed that early motor processes of driver take-over (i.e. hand and foot movements, redirecting the gaze at the roadway) might be mostly reflexive with little influence of the driver's mental state. In contrast, the time the driver needs for an intervention in vehicle control appeared to be affected by the driver's cognitive processing and his mental state. This goes hand in hand with results reported by Ruscio et al. (2015) which show that expecting an event influences the time needed for perceiving and mentally processing a warning stimulus. However, expectation does not seem to affect the preparation and execution of a motor reaction in manual driving.

These findings suggest that motor processes and cognitive processing proceed partially in parallel, which is in line with Wickens' (1984) multiple resource theory. According to this theory, tasks can be processed concurrently as long as they do not require the same processing resources. Further examination of these assumptions is needed, with a special focus on non-driving related tasks. As the drivers' willingness to engage in secondary tasks was found to increase with higher levels of automation (Carsten et al., 2012; De Winter et al., 2014; Llaneras et al., 2013), it is vital to gain understanding of their impact on driver take-over. If the driver's mental state generally has little effect on the execution speed of motor processes, the same should hold for driver distraction.

1.3. Non-driving related tasks while automated driving

Studies on manual driving clearly show the vast impact of the performance of secondary tasks on road safety (e.g., Dingus et al., 2006; Engström et al., 2005; Greenberg et al., 2003; Horrey and Wickens, 2007). However, it remains unclear whether these findings can easily be transferred into the domain of automated driving.

Engagement in visually demanding secondary tasks during manual driving may cause cognitive overload (Gugerty et al., 2004; Ma and Kaber, 2005; Neubauer et al., 2012). However, as automation decreases mental workload (Ma and Kaber, 2005; Stanton et al., 2001), it remains uncertain how the reduced load level interacts with the execution of secondary tasks. In fact, Young and Stanton (2002a) warn that cognitive underload caused by automation "is at least as serious an issue as overload" (p. 179). In the Malleable Attentional Resources Theory, they propose that the capacity of attentional resources is to some extent adaptive to the task demands, and automation thus leads to a temporary reduction of the accessible attentional resources. When faced with an automation failure, the operator's limited maximum capacity may not allow the situation to be dealt with appropriately, leading to performance degradation (Young and Stanton, 2002a,b). In line with that, Neubauer et al. (2012) report that the use of a cell phone leads to a decrease in response times during automated driving. They conclude that secondary tasks counteract the mental underload caused by automation and maintain the driver's alertness. Participants drove either manually or in an automated mode, and either with or without secondary tasks on urban and cross-country roads. It was found that secondary tasks delayed braking response times to an emergency event during manual driving. For automated driving, however, drivers with a secondary task reacted faster compared to drivers without a secondary task. Consequently, it remains unclear how different levels of mental workload generated by secondary tasks affect driver take-over following conditionally automated driving. Especially the relationship between perceived mental workload and take-over performance requires further examination.

Additionally, more attention should probably be paid to the type of secondary task. Most studies on automated driving use artificial or standardized tasks (e.g., the Surrogate Reference Task, Gold et al., 2013; Radlmayr et al., 2014; or quiz-like games, Merat et al., 2012). It is not clear whether these tasks induce a demand that is comparable to what drivers might actually be doing while driving automated vehicles in the future. The choice between standardized and naturalistic secondary tasks is mostly a trade-off between experimental control and ecological validity. Standardized tasks usually allow better control of task demands by specifically inducing different levels of cognitive, visual, or auditory load. Unfortunately, naturalistic secondary tasks do not necessarily have the same effects on manual driving as artificial tasks (Shinar et al., 2005; Young et al., 2003). For instance, Shinar and colleagues

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