Applied Ergonomics 60 (2017) 116–127

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Effects of platooning on signal-detection performance, workload, and stress: A driving simulator study

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ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form
19 October 2016
Accepted 31 October 2016

Keywords:
Psychophysiology
Automated driving
Vigilance
Monitoring
Supervisory control
Out-of-the-loop

ABSTRACT

Platooning, whereby automated vehicles travel closely together in a group, is attractive in terms of safety and efficiency. However, concerns exist about the psychological state of the platooning driver, who is exempted from direct control, yet remains responsible for monitoring the outside environment to detect potential threats. By means of a driving simulator experiment, we investigated the effects on recorded and self-reported measures of workload and stress for three task-instruction conditions: (1) No Task, in which participants had to monitor the road, (2) Voluntary Task, in which participants could do whatever they wanted, and (3) Detection Task, in which participants had to detect red cars. Twenty-two participants performed three 40-min runs in a constant-speed platoon, one condition per run in counterbalanced order. Contrary to some classic literature suggesting that humans are poor monitors, in the Detection Task condition participants attained a high mean detection rate (94.7%) and a low mean false alarm rate (0.8%). Results of the Dundee Stress State Questionnaire indicated that automated platooning was less distressing in the Voluntary Task than in the Detection Task and No Task conditions. In terms of heart rate variability, the Voluntary Task condition yielded a lower power in the low-frequency range relative to the high-frequency range (LF/HF ratio) than the Detection Task condition. Moreover, a strong time-on-task effect was found, whereby the mean heart rate dropped from the first to the third run. In conclusion, participants are able to remain attentive for a prolonged platooning drive, and the type of monitoring task has effects on the driver's psychological state.

1. Introduction

The concept of a platoon—an actively coordinated, tightly spaced group of vehicles traveling together (Bergenhem et al., 2012; Ren and Green, 1994)—has been studied for several decades (e.g., Fenton et al., 1968; Thorpe et al., 1998). Because the vehicles in a platoon are driving with short yet constant headways, substantial benefits are achieved in terms of safety, traffic flow efficiency, and energy consumption (Hochstädter and Cremer, 1997; Karaaslan et al., 1991; Kunze et al., 2011; Tsugawa et al., 2011). Now that sensor, computer, and communication technologies are advancing rapidly, platooning is gaining interest among engineers (e.g., Larson et al., 2015; Ploeg et al., 2014) and Human Factors scientists (e.g., Gouy et al., 2014; Skottke et al., 2014).

Platooning often entails both longitudinal and lateral automation (e.g., Bergenhem et al., 2012), and hence no direct inputs by the driver are required. According to current legal frameworks, the driver must always be able to resume manual control (Kim et al., 2016; United Nations, 1968). Thus, the role of the driver in a platoon is, at present, ill-defined with, on the one hand, an exemption from control duties and, on the other, the ever-present requirement to be able to reclaim control (see also Norman, 2015). Unless the automated driving technology is legally allowed to drive in *all* environmental circumstances and is *perfectly* capable and reliable (or can always bring itself to a minimal-risk condition; Society of Automotive Engineers, 2014), the possibility remains that the driver has to take over control or modify the automation mode, set-points, or control laws (see also Sheridan, 2011).

Researchers have expressed concerns about the effects of platooning on the driver's psychological state (e.g., Levitan et al., 1998; Saffarian et al., 2012). Because the driver in a platoon is supervising the automation rather than manually controlling the car, there is

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http://dx.doi.org/10.1016/j.apergo.2016.10.016
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the risk of becoming drowsy, mentally underloaded, and fatigued (Cha, 2003; De Waard et al., 1999; Saxby et al., 2013; Young and Stanton, 2007). Although automated driving is experienced as effortless, at the same time the drivers are subjected to pressure because they have to remain alert in order to be able to intervene in a critical scenario (Banks et al., 2014; Casner et al., 2016). In fact, the notion that the vehicle is in control but the driver remains responsible for accidents that may occur has been said to be "a formula for extreme stress" (Hancock, 2015, p. 138). Furthermore, research has shown that when participants are tasked to monitor a machine in order to detect irregular events, they become frustrated and stressed (Scerbo, 2001; Szalma et al., 2004; Warm et al., 2008).

A common adage within the Human Factors domain is that humans are poor monitors (Hancock and Parasuraman, 1992; Kibler, 1965; Harris, 2002; Pritchett and Lewis, 2010; Sheridan, 1996; Wiener and Curry, 1980), or as Wiener (1985) put it: "After three decades of highly prolific research on human vigilance (Mackie, 1977), we are still making the seemingly contradictory statement: a human being is a poor monitor, but that is what he or she ought to be doing." (p. 87). Farber (1999) pointed out that platooning drivers are unable to remain attentive for prolonged periods and will invariably engage in non-driving tasks. Empirical evidence concurs that drivers of automated vehicles are likely to engage in tasks such as calling on the phone, reading, interacting with a smartphone, or grabbing something from the rear compartment, making them unable to react in time if an emergency happens (Llaneras et al., 2013; Omae et al., 2005). It is for this reason that Google removed the steering wheel from their driverless cars (Teller, 2015). However, it is yet unknown whether Google's form of function allocation, in which the human is engineered out of the control loop, is tenable or legally acceptable (Kim et al., 2016). It certainly runs at odds with how automation has been deployed in complex systems such as aviation, water transport, and process control (see Sheridan, 2002).

Thus far, there appears to be no empirical evidence regarding the psychological state of platooning drivers as a function of monitoring task conditions. Moreover, much of what has been said of humans being poor monitors is based on experiments in which subjects sat in an isolated booth and responded to irregular stimuli having a low signal-to-noise ratio (cf. the highly-cited vigilance experiments by Mackworth, 1948). It is unclear to what extent the results of the classical vigilance paradigm generalize to complex supervisory tasks (Kibler, 1965; Stearman and Durso, 2016). According to a literature review by Cabrall et al. (2016), there is little overlap between the features of classic vigilance research and published experimental tasks of driving vigilance. A driving simulator study by Funke et al. (2007) found that drivers of a semi-automated vehicle actually performed *better* in a pedestrian-detection task than drivers in a manual control condition. Similarly, an on-road study by Davis et al. (2008) showed a performance improvement in target-detection performance for automated convoy driving as compared to manual convoy driving.

1.1. Present research

The aim of the present research was to investigate how the monitoring task of drivers in a platoon influences dimensions of stress, workload, and signal-detection performance. Participants were told that a critical situation may occur and that they had to intervene when needed. Three task instructions were compared: (1) 'No Task' (NT), in which no extra task was to be performed, (2) 'Voluntary Task' (VT), in which it was emphasized to the participants that they were free to do whatever they wanted, and (3) 'Detection Task' (DT), in which participants were asked to detect red cars among other traffic in the road environment. The NT condition assessed the effects of monitoring demands that are similar to those that occur with modern forms of highly automated driving in which drivers should be vigilant for events that the automation cannot handle. The DT condition added extra task demands on top of the baseline monitoring demands, requiring the participant to scan cars in the environment. Conversely, the VT condition created a less demanding situation, allowing the driver to engage in non-driving tasks. The experiment was conducted in a driving simulator, providing a safe and controlled environment in which the traffic behaves identically for all participants.

Based on the aforementioned literature, we expected that the DT condition would yield the highest and the VT condition the lowest scores on stress and workload. In our study, stress dimensions (engagement, distress, & worry) were operationalized with the multi-dimensional Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999), whereas aspects of workload were assessed with the NASA Task Load Index (TLX). Additionally, we used cardiovascular measures, whereby heart rate was regarded as an indication of stress (Healey and Picard, 2004), and heart rate variability was regarded as an indication of workload (Brookhuis and De Waard, 2010; Cinaz et al., 2013; Fallahi et al., 2016; Jorna, 1992; Luque-Casado et al., 2016; Suriya-Prakash et al., 2015). Moreover, considering the literature about human vigilance performance, we expected that participants in the DT condition would miss a substantial number of red cars. An eye tracker was used to record the percentage of eye-closure as an indicator of task engagement (cf. Lal and Craig, 2002; Körber et al., 2015; Wierwille et al., 1994).

2. Method

2.1. Participants

Twenty-two participants (13 male) aged between 19 and 45 years ($M = 29.6$; $SD = 6.8$) with at least 1 year of driving experience ($M = 10.0$; $\mathrm{SD} = 6.7$) were recruited. Most participants were from the University of Southampton community, with 14 participants being students, researchers, or lecturers at the university, a further four holding an engineering qualification, two being administrators, one being a medicine student, and one a police officer who indicated that driving is part of his profession. In order to retain a typical driving population, we did not apply exclusion criteria regarding personal characteristics that are known to be associated with heart rate variability, such as being a smoker (Barutcu et al., 2005) or general fitness level (Corrales et al., 2012; Luque-Casado et al., 2013). However, being healthy and having 20/20 vision were inclusion criteria, and given the acute effects of smoking on heart-rate variability (Karakaya et al., 2007; Manzano et al., 2011), we verified that none of the participants engaged in smoking in between the experimental sessions. Five participants indicated they drove less than once a month, five once a month, three 1–3 days a week, three 4–6 days a week, and six every day in the past 12 months. Seven participants indicated they drove 1–1000 miles, three 1001–5000 miles, six 5001–10,000 miles, four 10,001–20,000 miles, one 20,001–30,000 miles, and one over 50,000 miles in the past 12 months.

All participants in this experiment read and signed a consent form. The study was approved by the Ethics and Research Governance Online of the University of Southampton under submission ID number 13967.

2.2. Apparatus

The experiment was performed in the Southampton University Driving Simulator (SUDS; Fig. 1), a Jaguar XJ Saloon. The simulator ran on STISIM Drive® 3, which is a widely used driving simulator