Carryover Effects of Highly Automated Convoy Driving on Subsequent Manual Driving Performance

Eva-Maria Skottke, HMKW, Campus Cologne, Germany and RWTH Aachen University, Aachen, Germany, **Günter Debus** and **Lei Wang**, RWTH Aachen University, Aachen, Germany, and **Lynn Huestegge**, RWTH Aachen University, Aachen, Germany and University of Würzburg, Würzburg, Germany

Objective: In the present study, we tested to what extent highly automated convoy driving involving small spacing ("platooning") may affect time headway (THW) and standard deviation of lateral position (SDLP) during subsequent manual driving.

Background: Although many previous studies have reported beneficial effects of automated driving, some research has also highlighted potential drawbacks, such as increased speed and reduced THW during the activation of semiautomated driving systems. Here, we rather focused on the question of whether switching from automated to manual driving may produce unwanted carryover effects on safety-relevant driving performance.

Method: We utilized a pre–post simulator design to measure THW and SDLP after highly automated driving and compared the data with those for a control group (manual driving throughout).

Results: Our data revealed that THW was reduced and SDLP increased after leaving the automation mode. A closer inspection of the data suggested that specifically the effect on THW is likely due to sensory and/or cognitive adaptation processes.

Conclusion: Behavioral adaptation effects need to be taken into account in future implementations of automated convoy systems.

Application: Potential application areas of this research comprise automated freight traffic (truck convoys) and the design of driver assistance systems in general. Potential countermeasures against following at short distance as behavioral adaptation should be considered.

Keywords: highly automated driving, platooning, traffic safety, driver assistance systems, carryover effects, adaptive cruise control, behavioral adaptation, time headway, SDLP

Address correspondence to Eva-Maria Skottke, HMKW (Campus Cologne), Department of Media & Business Psychology, Höninger Weg 139, 50969 Köln, Germany; e.skottke@hmkw.de.

HUMAN FACTORS
201X, Vol. XX, No. X, Month XXXX, pp. 1–12
DOI: 10.1177/0018720814524594

OBJECTIVE AND BACKGROUND

Systems that support or automate parts of the driving task are part and parcel of modern automobiles. Some research groups predict that full vehicle automation may be implemented on roads as soon as 2030 (e.g., Walker, Stanton, & Young, 2001, with respect to British roads). Current technical implementations mainly differ in the degree of automation. For example, simple cruise control assists the driver in maintaining constant speed, whereas modern (semiautomatic) adaptive cruise control (ACC) systems utilize distance information to keep speed with the vehicle in front, typically by controlling both acceleration and braking responses of the car. Probably the most advanced technical implementation of automated driving is known as the automated highway system (AHS), or "platooning." These terms refer to "a system that combines vehicle and roadway instrumentation to provide some level of automated ('hands-off/feet-off') driving" (e.g., Levitan & Bloomfield, 1998). Thus, this transportation system allows the road infrastructure to guide the vehicle automatically in place of the driver. Specifically, electronic devices are used for communication purposes through satellites, linking the cars to the infrastructure. As a consequence, the system allows many vehicles to accelerate or brake simultaneously and to follow each other with small distances ("electronic drawbar").

In recent years, several potential implementations of automated driving have been the subject of intense research (Merat & Lee, 2012). Examples of recent European projects include the Have-it project coordinated by Continental, SARTRE (http://www.sartre-project.eu), CityMobil (http://www.citymobil-project.eu), and EASY, a project funded by the U.K. research

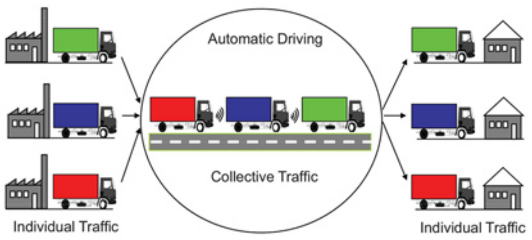

Figure 1. Scenario for electronically coupled truck convoys on parts of the driving route as envisioned within the KONVOI project. Source: Henning and Preuschoff (2003). Reprinted with permission.

council. The present study was developed as an offspring of an earlier German project KONVOI (RWTH Aachen University, 2005–2009, funded by the German Ministry for Education and Research), which was specifically aimed at studying the automation of truck convoys (freight traffic) on parts of their driving route (see Figure 1). Typically, a vehicle in the leading position would be followed by other vehicles at very small distances. The automation covers the leadership of the track and the regulation of both distance and speed during the (highly automated) convoy trip.

Potential benefits of highly automated driving comprise economical and ecological aspects in terms of increased efficiency, predictability of trip times, and reduced environmental pollution due to a decrease in fossil fuel consumption and emissions (Levitan & Bloomfield, 1998). In contrast, there may be concerns with respect to the driver's behavior and acceptance regarding comfort- and safety-related issues. In the present study, we focus on potential carryover effects when switching from automated driving to manual driving and present some exploratory data on drivers' overall acceptance of automated convoy driving.

Several studies have shown that automation systems may cause changes in driving behavior. These studies, which are mainly concerned with ACC systems, basically focus on behavioral adaptations to automation systems during the time in which these systems are activated (Rudin-Brown & Jamson, 2013). Although in basic research the concept of (sensory and behavioral) adaptation typically refers to the change in responsiveness due to sustained stimulation (e.g., Wark, Lundstrom, & Fairhall, 2007), a broader definition of adaptation with respect to road user behavior was proposed by the OECD Research Group (1990):

> Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change; behavioural adaptations occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result; they create a continuum of effects ranging from a positive increase in safety to a decrease in safety. (p. 23; also see Fuller, 1984; Summala, 1997; Vaa, 2013; Wilde, 1988)

More specifically, previous studies on adaptation during activated ACC systems have reported several safety-relevant effects on cognition and behavior. For example, Stanton and Young (2005) observed reduced situation awareness as a byproduct of ACC. Hoedemaeker and Brookhuis (1998) reported that drivers showed increased speed and braking force as well as smaller minimum time headway (THW; also see Ward, Fairclough, & Humphreys, 1995). Heino, Rothengatter, and Van der Hulst (1995) found decreased THW, too, and also reported greater THW variability. Rudin-Brown and Parker (2004) reported that ACC systems evoked behavioral adaptation in terms of changes in workload and driving performance, including impaired lane-keeping performance (standard deviation of lateral position; SDLP). A meta-analysis of behavioral effects of ACC lends further support to the claim that increased speed and decreased THW are major effects of automated systems (Dragutinovic, Brookhuis, Hagenzieker, & Marchau, 2005; for a brief overview, also see Saad et al., 2005).

Although the studies focused on behavioral adaptation during the activation of automation systems, much less is known about potential carryover effects on manual driving after deactivation of the automated driving mode. For example, Levitan and Bloomfield (1998) demonstrated carryover effects after being engaged in an AHS if vehicle control was passed to the driver at a relatively high speed in the automated lane. Under these conditions, participants drove much faster than the stipulated speed limit after entering the nonautomated lane (also see de Vos, Theeuwes, Hoekstra, & Coemet, 1998). Similarly, a dual-task study by Merat, Jamson, Lai, and Carsten (2012) showed that regaining control of driving is specifically problematic under high cognitive demands. Wille, Röwenstrunk, and Debus (2008) reported data from a simulator study with professional truck drivers, suggesting that SDLP significantly increased after driving in an automated truck convoy. Another simulator study from our own research group (Eick & Debus, 2005) suggested first evidence that participants who were engaged in a platoon scenario with small distances to the front vehicle (i.e., 0.3 s THW) subsequently chose risky distances of up to 0.5 s (equivalent to 14 m when driving at 100 km/h) in the post automated manual driving phase. However, the data from this study could not definitely be explained in terms of adaptation processes, and may well have resulted from time-on-task effects. Note that both THW and SDLP measures are highly relevant for traffic safety. Although small distances are directly associated with indicators of risky driving (e.g., time to collision), SDLP is typically associated with variables related to the amount of "weaving" of the car (Verster & Roth, 2011) and driver distraction (e.g., Knappe, Keinath, & Meinecke, 2008).

The present simulator study utilized a pre–post design to present new data on potential carryover effects of automated convoy driving involving small spacing ("platooning") on safety-relevant behavioral parameters. Although previous studies on behavioral adaptation in traffic have often addressed processes occurring on larger time scales (e.g., in terms of a generalized behavioral response to new technology; see Grayson, 1996; Rudin-Brown & Jamson, 2013), we here study more transient carryover effects on manual driving performance immediately subsequent to automated driving. Such carryover effects might be based on low-level sensory adaptation (i.e., drivers might get used to small spacing and subsequently exhibit a tendency to underestimate spatial distance), or on higher-level learning processes (i.e., drivers might experience that small spacing during automation did not yield hazardous events, and subsequently adopt a more risky driving strategy; see risk homeostasis theory by Wilde, 1988, 2013). (It should be noted that some claims of risk homeostasis theory have recently been challenged. In particular, the idea that people are constantly monitoring risk levels has been questioned in that there is more support for threshold models [see, e.g., Lewis-Evans, de Waard, & Brookhuis, 2013].) Thus, we hypothesized that automated driving with small spacing may lead to significantly reduced THWs during subsequent manual driving.

We simultaneously analyzed two parameters, namely THW and SDLP, and specifically focused on their time course during pre- and postautomated driving to reveal the underlying mechanisms of potential behavioral changes. In addition, we implemented a control group (involving manual driving throughout) to control for potential time-on-task effects. Although previous literature on manual driving has reported evidence for an increase of THW with time on task (Van der Hulst, Meijman, & Rothengatter, 2001), we reasoned further empirical support would strengthen our rationale. We also administered ratings and a questionnaire to explore drivers' overall acceptance of the automation system.

MATERIAL AND METHOD

Research Design

In the automated driving group, participants underwent three phases, a baseline preautomated (manual) driving period, an automated driving period, and a postautomated (manual) driving period. To study potential adaptation effects, manual driving period (pre vs. post) served as an independent variable. In the control group, participants were engaged in manual driving throughout. To allow for a valid group comparison (automated driving group vs. control group), the whole (manual) driving distance of the control group was divided into three sections corresponding to those in the automated driving group (see the discussion later). Dependent variables comprised mean and minimum

THW as well as SDLP. For the main analyses, *t* tests and ANOVAs were applied with an alpha level of 5%.

Participants

In the automated driving group, 11 male and 8 female academic students and employees took part. Their age ranged from 22 to 43 years (M = 29 years). In the control group, 22 participants (8 females) took part (age M = 24 years, range = 22–29). Most of the participants had prior experience with driving simulators and were paid for participation. In both groups participants had normal vision and were naïve with respect to the purpose of the study.

Figure 2. Screenshot of the simulator scene (participant's view) during manual car following.

Facilities and Apparatus: The Driving Simulator

The automated driving group was tested at the Centre for Traffic Sciences at the University of Würzburg. The control group was added later in time and tested at RWTH Aachen University. The driving simulators were equipped with the same simulator software (SILAB, see www.silabsoft.org) and consisted of a motion system including a Steward platform (a type of parallel robot that incorporates six prismatic actuators) with 6° of freedom (Hexapod), and three passive pneumatic actuators. The display system covered 180° of the field of vision (horizontally) projected onto a spherical screen. The driver was seated in a fully equipped car. Traffic variables (e.g., oncoming traffic) and behavioral parameters (THW, SDLP) were recorded by the simulator software with a sampling frequency of 100 Hz.

Traffic density in the simulation was low. The traffic was characterized by monotonously oncoming passenger cars, which were the only type of vehicles on the road. Most of the road sections were straight (including a few curves), but no intersections or other possibilities for exit were involved. Only one lane (width: 3.5 m) was available, thus no cars passed the platoon. Lane markings, trees, little hills, and a few road signs were displayed. The same simulated driving environment was used for manual and automated driving periods. Participants were able to see over the leading vehicle (blue VW Golf, width: 1.66 m) during manual and automated driving mode. No other cars were seen in front of the leading car (see Figure 2). All participants were monitored during their simulator drive, and none of them performed any secondary tasks during the automated mode.

Procedure

In the driving simulator, participants were engaged in a nonautomated driving mode (preautomated period, 12 km) before they switched to automated convoy driving (33 km). Crucially, after automated driving they switched back to a nonautomated driving mode (postautomated period, 12 km). In the manual preautomated period, participants were instructed to follow the car in front. Specifically, they were told that the driver in front of them was the only person knowing the correct way to reach a notional destination (thus, overtaking was prevented). Participants were free to choose their individual speed and THW, whereas the car in front was set to a fixed speed of 100 km/h. The subsequent automated mode was initiated by activating two systems: the ACC, regulating both speed and following distance, and heading control (HC), assisting the driver in his or her lateral tracking task. Together, these systems represent a high level of driving automation. During the automated phase the cars were coupled with very short THWs of 0.3 s (equivalent to 8 m while driving at 100 km/h). Note that the benefits of automated driving mentioned in the introduction (e.g., reduced fuel consumption and pollution) call for such very short THWs. The coupling period also involved a constant speed of 100 km/h. In the middle of this period (after 16.5 km) participants were involved in ratings (utilizing 15-point Likert-type scales ranging from 1 = *not at all* to 15 = *highly*) with respect to boredom, fatigue, and difficulty. Rating questions were presented orally by the investigator (using loudspeakers), whereas the corresponding scale was visually present on a paper sheet attached to the middle of the steering wheel. Participants responded orally to the rating questions, and their answers were recorded via microphones. The rating scales (and the corresponding paper sheet) were explained to the participants prior to the simulator drive. An additional overall rating concerning the comfort and acceptance of highly automated driving (in the automated driving group only) was conducted after the experiment and outside the simulator.

The automated driving period ended by deactivation of both systems (ACC and HC), announced by the investigator through loudspeakers. After deactivation, the car in front accelerated to produce a comparatively large distance to the participant's car. Drivers were instructed to take over the control of their own car, and to indicate when they reached their intended distance to the car in front. This was accomplished by all participants within the first 2 km after decoupling. The automated driving mode covered a longer distance than the manual driving modes to ensure that participants had a reasonable amount of time to adapt to the automated mode.

In the control group, participants were given the same instructions but they were driving 60 km without any assistance (i.e., comparable to the manual periods in the automated driving group). All environmental conditions (e.g., velocity of the leading car, road conditions, oncoming traffic) were comparable to the automated driving group, and they were also involved in the same rating procedure during driving at the corresponding point in time.

RESULTS

THW and SDLP

For a general pre–post comparison in the automated driving group, the first 2 km of the preautomated period were defined as exercising distance and excluded from the analysis. Similarly, the first 2 km of the postautomated period (i.e., the decoupling phase) were excluded. For aggregation of the THW data, we averaged across all THW data samples within each route section of interest (or, for more fine-grained analyses, for sections of 2 km; see the discussion later). SDLP was computed by using a variable coding the car's distance to the outer traffic lane markings. SDLP represents the standard deviation of all corresponding data samples within each route section of interest.

Crucially, THW was significantly reduced from preautomated period (mean THW = 2.7 s, mean minimum THW = 1.5 s) to postautomated period (mean THW = 2.1 s, mean minimum THW = 1.1 s), $t(18) = 3.26$, $p < .05$, $d = 0.87$, and $t(18) = 2.83$, $p < .05$, $d = 0.76$, respectively. Single participants even exhibited THW of 0.5 s after automated convoy driving.

One problem with the present pre–post design is that a reduction of THW in the postautomated period may not be specifically due to the automated phase, but simply represent a time-on-task effect (e.g., see de Waard & Brookhuis, 1991). Thus, the lower values in the postautomated period may simply represent the end of the tail of a monotonically decreasing THW function (even though previous research rather suggested a positive correlation of time on task and THW; see Van der Hulst et al., 2001). To explicitly test this alternative explanation, we first implemented a more fine-grained analysis of THW for small (2 km) sections 10 km before and 10 km after decoupling from automated driving. Note that a time-on-task effect should be reflected in a decrease of THW in both the preautomated and postautomated period (or, alternatively, a flat distribution in the postautomated period). However, we found opposite linear trends in THW distributions before and after automated driving. Although THW systematically decreased during the preautomated period, $F(4, 72) = 4.73$, $p < .05$, we observed a significant linear increase in the postautomated period, $F(4, 72) = 4.69$, $p < .05$, which is the first evidence against a time-on-task explanation. Of interest, THW at the end of the postautomated automated driving phase rose to about the same

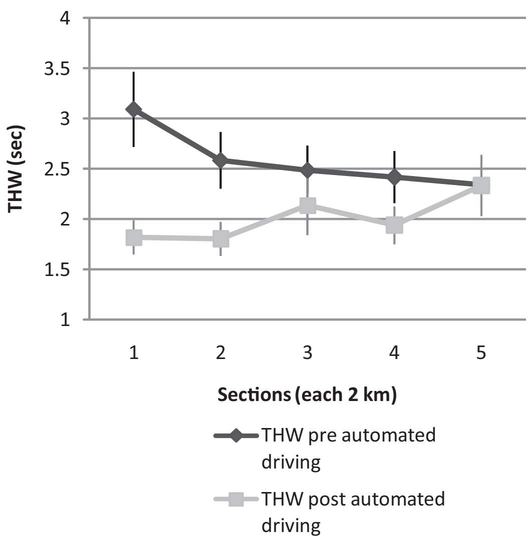

Figure 3. Fine-grained analysis of time headway (THW) pre– and post–automated driving in the automated driving group.

level as THW at the end of the preautomated period (see Figure 3), suggesting that participants appear to recover their preferred THW level about 10 km after decoupling from the automated phase. This observation also suggests that the length of the postautomated driving section was sufficiently long to track this process of recovery.

In addition, we compared pre- and post-THW results between groups by analyzing exactly the same road sections. A mixed 2 × 2 ANOVA with group as a between-subjects factor and period (pre and post critical phase) as a within-subject factor resulted in a significant interaction of group and period for mean and mean minimum THW (Figure 4), $F(1, 21) = 12.61$, $p < .001$ for mean THW, and $F(1, 21) = 6.58$, $p < .05$ for mean minimum THW. Thus, we did not observe a reduction of THW as a function of time on task in the control group, a finding that clearly rules out time on task as an alternative explanation of the adaptation effects.

In addition, an analysis of the complete driving route in the control group revealed that THW in the control condition systematically increased over time (Figure 5), which was indicated by a significant linear trend, $F(5, 105) = 4.18$, $p < .05$ (see Van der Hulst et al., 2001, for similar results).

SDLP in the automated driving group significantly increased from 0.18 m in the preautomated period to 0.22 m in the postautomated period (i.e., after automated driving), $t(18) = 4.51$, $p < .001$, $d = 0.9$. Again, we also analyzed exactly the same driving sections in the control group and compared them to the data in the experimental condition. Unlike the THW results, there was no significant interaction between period and group and no significant main effect of group, both $F < 1$. We observed a significant main effect only of period

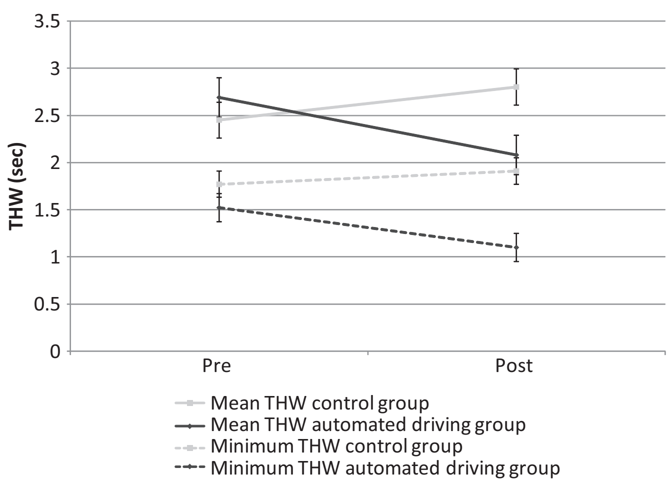

Figure 4. Mean and mean minimum time headway (THW) of the automated driving group and the control group pre– and post–critical road section.

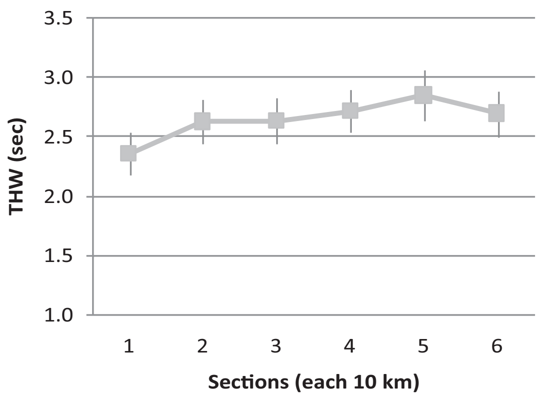

Figure 5. Mean time headway (THW; including *SE*) for 10 km sections (60 km overall) during manual car following in the control group.

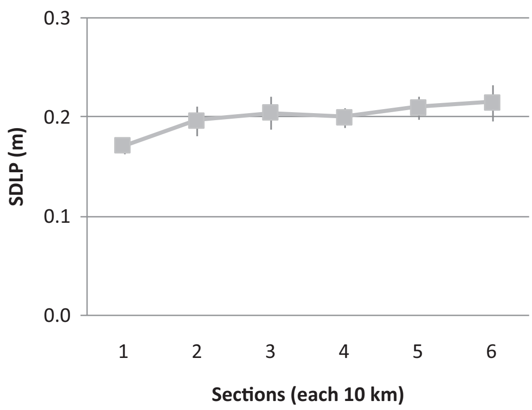

Figure 7. Mean standard deviation of lateral position (SDLP; including *SE*) for 10 km sections in the control group.

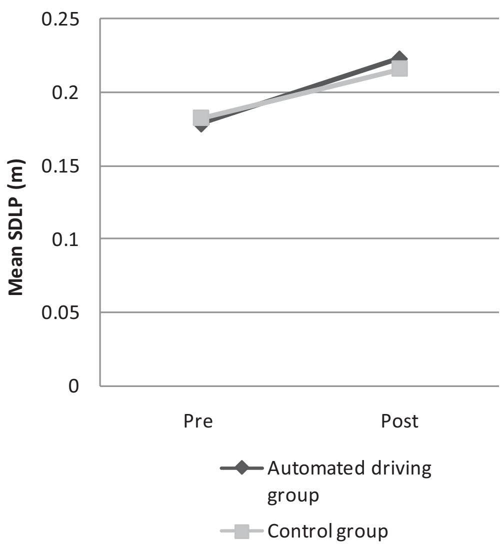

Figure 6. Mean standard deviation of lateral position (SDLP) for both groups during pre and post periods.

(increase from pre to post), $F(1, 21) = 30.84$, $p < .01$, which thus appears to reflect a time-on-task effect (Figure 6).

In line with these data, the analysis of SDLP over the whole driving route in the control group showed a systematic increase over time, $F(5, 105) = 9.52$, $p < .05$ (Figure 7).

Explorative Rating and Questionnaire Data: Mental State and Acceptance

Rating data (using a 15-point Likert-type scale from 1 = *not at all* to 15 = *highly*) referred to perceived boredom, fatigue, and difficulty of the driving task in the middle of the automated phase and at the corresponding point in time in the control group. Although it appears difficult to clearly interpret the mean values given the absence of normative data, our attempt to associate verbal descriptors to the scale values may justify drawing at least some preliminary conclusions. Specifically, we observed relatively high ratings for boredom (automated: $M = 12.5$, $SD = 2.0$; control: $M = 12.9$, $SD = 1.6$) and fatigue (automated: $M = 9.3$, $SD = 3.6$; control: $M = 6.9$, $SD = 3.5$). The difficulty of the driving task was rated as being comparatively low (automated: $M = 4.3$, $SD = 2.3$; control: $M = 3.5$, $SD = 1.7$; see Figure 8). Only the group difference in fatigue was statistically significant, $t(38) = 2.19$, $p < .05$.

After simulator driving, participants in the automated driving group were further asked how comfortable and safe they would rank the automation system in general, and how close they perceived the distance during automated driving. As a result, more than half of the participants rated the automated driving system as being “highly uncomfortable,” whereas no one rated it as being “comfortable” (see Figure 9a). The distance during the automated coupling period was judged as “very close” by more than 80% of the participants (Figure 9b).

The majority of participants (67%) rated the automated system as being “safe” or “more safe than unsafe.” In contrast, only 10%

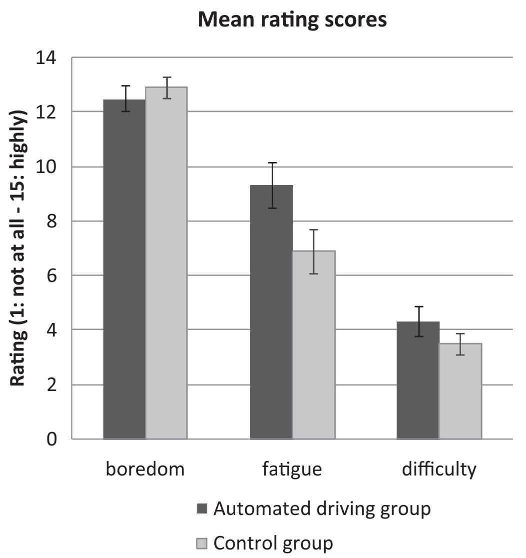

Figure 8. Participants' rating of their own state during highly automated driving and during manual driving in the control group.

considered the automated system as being "unsafe" (Figure 10).

DISCUSSION

In the present simulator study, we utilized a pre–post simulator design including a control group to study carryover effects of automated convoy driving involving small spacing ("platooning") on THW and SDLP during subsequent manual driving. In general, THW was reduced and SDLP increased after leaving the automation mode, replicating previous reports from our group (Eick & Debus, 2005; Wille et al., 2008). However, a closer inspection of the data and comparisons with the control group (which was involved in manual driving throughout) suggested that only the effect on THW could clearly be attributed to automated driving, representing a behavioral carryover effect that lasted for about 10 km after decoupling from the automated phase. Note that small THW is directly associated with indicators of risky driving (e.g., time to collision), so that these results potentially bear important implications for real-life implementations of AHS.

Unlike the THW data, the SDLP results across groups suggested that a time-on-task account would be quite in line with our data (see Verster & Roth, 2001, for similar results). SDLP is sometimes considered to be an indicator of drivers' distraction or inattentiveness (e.g., Knappe et al., 2008; Zwahlen, Adams, & DeBald, 1988), and it could well be that the observed increase of SDLP is a mere result of the long time participants spent driving in the simulator.

Overall, the present results are in line with results from other research groups reporting potentially negative carryover effects of automated driving on subsequent manual driving performance. Specifically, it was reported that ACC systems may lead to an increase in speed even after the control over the vehicle is completely passed to the driver again (e.g., de Vos et al., 1998; Levitan & Bloomfield, 1998). Our results also complement previous research that was mainly focused on behavioral effects of ACC during the automated phase itself (e.g., Dragutinovic et al., 2005; Heino et al., 1995; Hoedemaeker & Brookhuis, 1998; Rudin-Brown & Parker, 2004; Saad et al., 2005; Ward et al., 1995) and reported an increase in speed and decreased THW during active ACC.

The observed carryover effects of automated convoy driving on subsequent THW in manual driving may represent a behavioral change resulting from sensory and/or cognitive adaptation processes. In physiology the concept of (sensory or behavioral) adaptation typically refers to a change in (sensory or behavioral) responsiveness due to sustained stimulation (e.g., Wark et al., 2007). When transferring this concept of adaptation to the current driving setting, it may well be that the drivers in our study experienced sensory adaptation with respect to the small forced THW during the automation phase (representing a sustained stimulation). When leaving the automation mode, it is possible that participants perceive small THWs as being less small (or, alternatively, as less threatening) when compared to the preautomated period. Similar contextual effects are also known from other psychological domains. For example, a man who is six feet tall will look "tall" when surrounded by others of average height but "short" among a group of professional basketball players. Apparently, context may alter the frame of

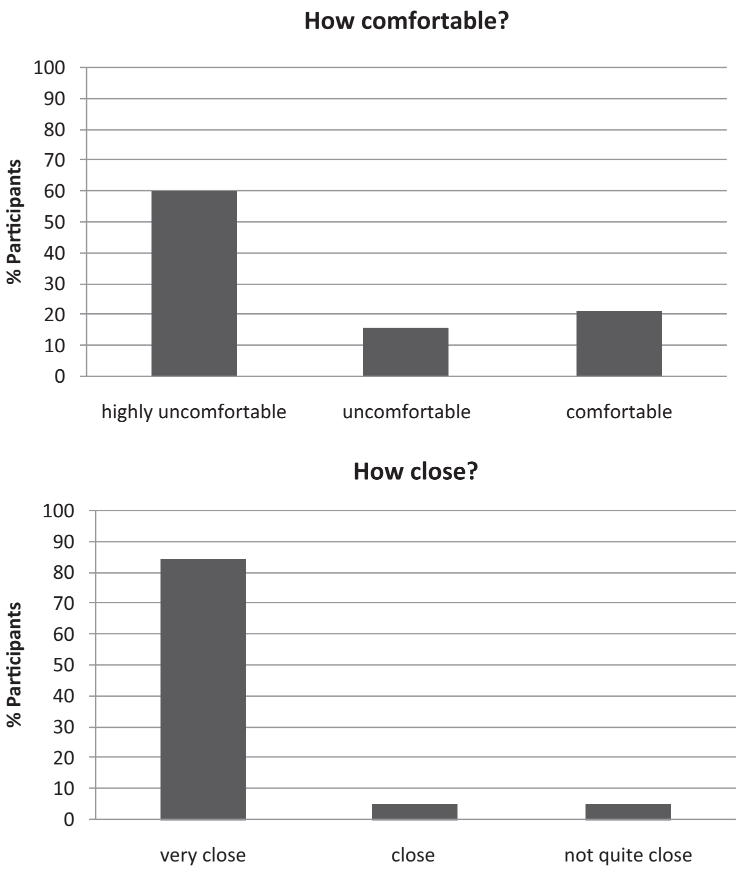

Figure 9. Participants' ratings of comfort and distance during highly automated driving.

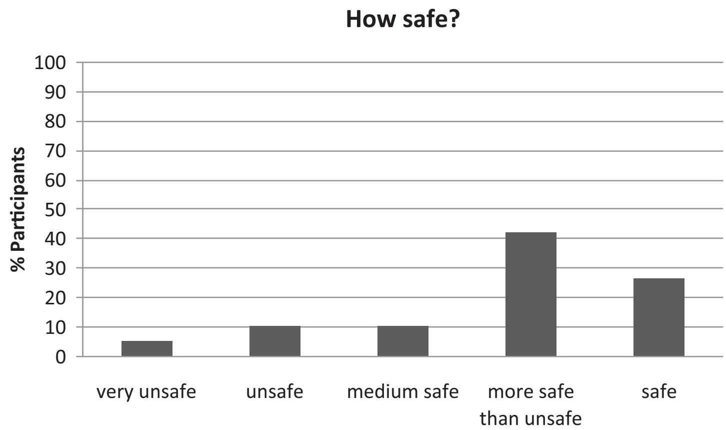

Figure 10. Participants' rating of the safety of highly automated driving.

reference and thus apparent size (e.g., Helson, 1947, 1964). In addition, psychophysical studies demonstrated that a continuous lack of stimulus change may reduce perceptual abilities (e.g., Lauterbach & Sarris, 1980). However, it should be noted that the traffic simulation utilized in the present study exhibited comparatively low traffic density, which might have increased the drivers' tendency to keep short THWs.

An alternative underlying mechanism for our observed adaptation effect could be based on learning processes. More specifically, drivers may have associated small THW with the absence of hazardous events during automated driving, and this experience may implicitly or explicitly carry over to subsequent manual driving, resulting in an altered perceived field of safe travel (Gibson & Crooks, 1938) and eventually in a riskier driving strategy (see Wilde, 1988, 2013). The current results also fit nicely into a broader framework of adaptation in traffic systems proposed by the OECD Research Group (1990), who defined adaptation as an unwanted behavioral response to the introduction of new traffic-related technical implementations (also see Rudin-Brown & Jamson, 2013). Although the introduction of automated convoy driving may well reduce the risk of accidents during the automated phase itself, there may also be unwanted risk-prone aftereffects that should be seriously considered in future technical implementations. Based on our present data, it appears important to highlight that single participants even seemed to completely adapt to the very small distance from the automated coupling period.

Many studies have shown that (semiautomatic) ACC systems are comfortable and trustworthy for drivers (Hoedemaeker & Kopf, 2001; Nilson, 1995). The perceived comfort even increased when ACC also involved automated braking. Rudin-Brown and Parker (2004) found that participants developed extensive trust in ACC, which was not even impaired by ACC failure. In a study by Vollrath, Briest, and Oeltze (2010) participants rated driving with ACC as being safer and less stressful than without. Unfortunately, acceptance studies of highly automated convoy driving are comparatively rare. For example, Levitan and Bloomfield (1998) examined the driver's acceptance in an AHS while driving with gaps between 1.8 m and 2.7 m and with velocities between 105 km/h and 200 km/h. Generally, drivers preferred larger gaps but felt equally comfortable at any speed. De Waard, van der Hulst, Hoedemaeker, and Brookhuis (1999) compared drivers' ratings before and after being exposed to the AHS. Of interest, acceptance did not change significantly after experience with the system. However, some drivers disliked the fact that they had no control over the vehicle.

The explorative rating data in the present study suggest that the potential safety-critical drawbacks are not seriously considered by the majority of participants. Although the distance during the automation phase was rated as being very close and the situation was mainly experienced as being uncomfortable and boring (also see Nilson, 1995; Rudin-Brown & Parker, 2004), about two thirds rated the automation system as being at least "more safe than unsafe." These findings suggest a need for further research on potential measures to increase drivers' awareness of potential dangers associated with highly automated driving.

CONCLUSIONS

Many innovations have been introduced in automotive technology during the past decades. Vehicles today involve an increasing amount of automation, which is, for example, reflected in the rising importance of (semiautomatic) ACC systems that sometimes even include THW feedback (Fairclough, May, & Carter, 1997). The current research further extends the degree of automation, representing a trend toward automatic vehicle control. Although these systems generally stand for significant advantages in many areas including traffic safety, the present study also revealed some hidden risks. Specifically, we showed that THW substantially decreased after automated driving. Thus, we recommend that behavioral adaptations resulting from automated driving should be taken into account in future implementations of AHS and highly automated convoy driving. As potential countermeasures against the observed carryover effects, we suggest cognitive trainings prior to exposure to automated driving (e.g., explicitly communicating the occurrence, scope, and risks of adaptation effects) and/or the implementation of warning signals (e.g., based on THW feedback) during decoupling from automated driving (e.g., Bao, LeBlanc, Sayer, & Flannagan, 2012; Muhrer, Reinprecht, & Vollrath, 2012).

KEY POINTS

- We demonstrate carryover effects of highly automated convoy driving.
- Our data show that behavioral adaptation of time headway occurs after switching from automated to manual driving.
- We report acceptance measures regarding highly automated driving.

REFERENCES

Bao, S., LeBlanc, D. J., Sayer, J. R., & Flannagan, C. (2012). Heavy-truck drivers' following behavior with intervention of an integrated, in-vehicle crash warning system: A field evaluation. *Human Factors*, *54*, 687–697.

de Vos, A. P., Theeuwes, J., Hoekstra, W., & Coemet, M. J. (1998). Behavioural aspects of automatic vehicle guidance. Relationship between headway and driver comfort. *Transportation Research Record*, *1573*, 17–22.

de Waard, D., & Brookhuis, K. A. (1991). Assessing driver status: A demonstration experiment on the road. *Accident Analysis and Prevention*, *23*, 297–307.

de Waard, D., Van der Hulst, M., Hoedemaeker, M., & Brookhuis, K. A. (1999). Driver behavior in an emergency situation in the automated highway system. *Transportation Human Factors*, *1*, 67–82.

Dragutinovic, N., Brookhuis, K. A., Hagenzieker, M. P., & Marchau, V. A. W. J. (2005). Behavioural effects of advanced cruise control use: A meta-analytic approach. *European Journal of Transport and Infrastructure Research*, *5*, 267–280.

Eick, E.-M., & Debus, G. (2005). Adaptation effects in an automated car-following scenario. In G. Underwood (Ed.), *Traffic and transport psychology. Theory and application* (pp. 243–255). Amsterdam, Netherlands: Elsevier.

Fairclough, S. H., May, A., & Carter, C. (1997). The effect of time headway feedback on following behaviour. *Accident Analysis and Prevention*, *29*, 387–397.

Fuller, R. (1984). A conceptualization of driving behaviour as threat avoidance. *Ergonomics*, *27*, 1139–1155.

Gibson, J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile-driving. *American Journal of Psychology*, *51*, 453–471.

Grayson, G. B. (1996). *Behavioural adaptation: A review of the literature* (TRL Rep. No. 254). Crowthorne, UK: TRL.

Heino, A., Rothengatter, J. A., & Van der Hulst, M. (1995). *Collision avoidance systems safety evaluation* (DRIVE II Project V2002, Deliverable Report 33, Workpackage 0016). Groningen, Netherlands: University of Groningen.

Helson, H. (1947). Adaptation-level as frame of reference for prediction of psychophysical data. *American Journal of Psychology*, *60*, 1–29.

Helson, H. (1964). *Adaptation level theory*. New York., NY: Harper & Row.

Henning, K., & Preuschoff, E. (2003). *Einsatzszenarien für Fahrerassistenzsysteme im Güterverkehr und deren Bewertung* [*Scenarios of driver assistance systems in freight traffic and their evaluation*] (Fortschritt-Berichte VDI, Reihe 12, Nr. 531). Düsseldorf, Germany: VDI-Verlag.

Hoedemaeker, M., & Brookhuis, K. A. (1998). Behavioural adaptation to driving with an adaptive cruise control (ACC). *Transportation Research Part F: Traffic Psychology and Behaviour*, *1*, 95–106.

Hoedemaeker, M., & Kopf, M. (2001, August). *Visual sampling behaviour when driving with adaptive cruise control*. Paper presented at the 9th International Conference on Vision in Vehicles, Brisbane, Australia.

Knappe, G., Keinath, A., & Meinecke, C. (2008). Die Sensitivität verschiedener Maße zur Fahrzeugquerregelung im Vergleich [Comparison of the sensitivity of different measures of lateral vehicle regulation]. In J. Schade & A. Engeln (Eds.), *Fortschritte der Verkehrspsychologie. Beiträge vom 45. Kongress der Deutschen Gesellschaft für Psychologie* (pp. 237–256). Wiesbaden, Germany: VS Verlag.

Lauterbach, W., & Sarris, V. (1980). *Beiträge zur psychologischen Bezugssystemforschung* [*Contributions to psychological research in reference systems*]. Bern, Switzerland: Huber.

Levitan, L., & Bloomfield, J. R. (1998). Human factors design of automated highway systems. In W. Barfield & T. A. Dingus (Eds.), *Human factors in intelligent transportation systems* (pp. 131–163). Mahwah, NJ: Lawrence Erlbaum.

Lewis-Evans, B., de Waard, D., & Brookhuis, K. A. (2013). Contemporary models of behavioural adaptation. In C. M. Rudin-Brown & S. L. Jamson (Eds.), *Behavioural adaptation and road safety: Theory, evidence and action* (pp. 35–60). Boca Raton, FL: CRC Press.

Merat, N., Jamson, A. H., Lai, F. C. H., & Carsten, O. (2012). Highly automated driving, secondary task performance, and driver state. *Human Factors*, *54*, 762–771.

Merat, N., & Lee, J. D. (2012). Designing automated vehicles with the driver in mind. *Human Factors*, *54*, 681–686.

Muhrer, E., Reinprecht, K., & Vollrath, M. (2012). Driving with a partially autonomous forward collision warning system: How do drivers react? *Human Factors*, *54*, 698–708.

Nilson, L. (1995). Safety effects of adaptive cruise control in critical traffic situations. In *Proceedings of the Second World Congress on Intelligent Transport Systems: Steps forward* (pp. 1254–1259). Yokohama, Japan: Vertis.

OECD. (1990). *Behavioural adaptations to changes in the road transport system*. Paris: Organization for Economic Co-operation and Development.

Rudin-Brown, C. M., & Jamson, S. L. (Eds.). (2013). *Behavioural adaptation and road safety: Theory, evidence and action*. Boca Raton, FL: CRC Press.

Rudin-Brown, C. M., & Parker, H. A. (2004). Behavioural adaptation to adaptive cruise control (ACC): Implications for preventive strategies. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*, 59–76.

Saad, F., Hjälmdahl, M., Cañas, J., Alonso, M., Garayo, P., Macchi, J., Nathan, F., Ojeda, L., Papakostopoulos, V., Panou, M., & Bekiaris, E. (2005). *Analysis of behavioural changes induced by ADAS and IVIS* (AIDE project, Contract No. IST-1-507674-IP). Retrieved from http://www.aide-eu.org/pdf/sp1_deliv_new/aide_d1_2_1.pdf

Stanton, N. A., & Young, M. S. (2005). Driver behavior with adaptive cruise control. *Ergonomics*, *48*, 1294–1313.

Summala, H. (1997). Hierarchical model of behavioural adaptation and traffic accidents. In J. A. Rothengatter & E. Carbonell Vaya (Eds.), *Traffic and transport psychology: Theory and application* (pp. 41–52). Oxford, UK: Pergamon.

Vaa, T. (2013). Psychology of behavioural adaptation. In C. M. Rudin-Brown & S. L. Jamson (Eds.), *Behavioural adaptation and road safety: Theory, evidence and action* (pp. 207–226). Boca Raton, FL: CRC Press.

Van der Hulst, M., Meijman, T., & Rothengatter, T. (2001). Maintaining task set under fatigue: A study of time-on-task effects in simulated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *4*, 103–118.

Verster, J. C., & Roth, T. (2001). Standard operation procedures for conducting the on-road driving test, and measurement of the standard deviation of lateral position (SDLP). *International Journal of General Medicine 4*, 359–371.

Vollrath, M., Briest, S., & Oeltze, K. (2010). *Auswirkungen des Fahrens mit Tempomat und ACC auf das Fahrverhalten* [*Effects of driving with cruise control and ACC on driver behavior*] (Berichte der Bundesanstalt für Straßenwesen, Unterreihe Fahrzeugtechnik, Heft F 74). Bremerhaven, Germany: Wissenschaftsverlag NW.

Walker, G. H., Stanton, N. A., & Young, M. S. (2001). Where is computing driving cars? A technology trajectory of vehicle design. *International Journal of Cognitive Ergonomics 5*, 21–33.

Ward, N. J., Fairclough, S. H., & Humphreys, M. (1995, November). *The effect of task automatisation in the automotive context: A field study of an autonomous intelligent cruise control system*. Paper presented at the International Conference on Experimental Analysis and Measurement of Situation Awareness, Daytona Beach, FL.

Wark, B., Lundstrom, B. N., & Fairhall, A. L. (2007). Sensory adaptation. *Current Opinion in Neurobiology*, *17*, 423–429.

Wilde, G. J. (1988). Risk hoemeostasis theory and traffic accidents: Propositions, deductions and discussion of dissension in recent reactions. *Ergonomics*, *31*, 441–468.

Wilde, G. J. S. (2013). Homeostasis drives behavioural adaptation. In C. M. Rudin-Brown & S. L. Jamson (Eds.), *Behavioural adaptation and road safety: Theory, evidence and action* (pp. 61–86). Boca Raton, FL: CRC Press.

Wille, M., Röwenstrunk, M., & Debus, G. (2008). KONVOI: Electronically coupled truck-convoys. In D. de Waard, F. O. Flemisch, B. Lorenz, H. Oberheid, & K. A. Brookhuis (Eds.), *Human factors for assistance and automation* (pp. 243–256). Maastricht, Netherlands: Shaker.

Zwahlen, H. T., Adams, C. C., & DeBald, D. P. (1988). Safety aspects of CRT touch panel controls in automobiles. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S. H. Taylor (Eds.), *Vision in vehicles II* (pp. 335–344). Amsterdam, Netherlands: Elsevier.

Eva-Maria Skottke is researcher in the field of man–machine interaction. Since October 2012 she has been a professor for media and business psychology at HMKW, Campus Cologne. She earned her PhD in psychology at RWTH Aachen University in 2007.

Günter Debus is emeritus professor of psychology at RWTH Aachen University. His research areas are traffic psychology and psychology of emotions. He earned his postdoctoral degree at the University of Düsseldorf in 1976.

Lei Wang is lecturer of psychology at RWTH Aachen University and member of the Department of Work and Cognitive Psychology. He earned his diploma in psychology at the Humboldt-University Berlin in 2009.

Lynn Huestegge is researcher in the field of visual cognition. He is professor of psychological methods, cognition, and applied research at University of Würzburg. He earned his PhD at the University of Bielefeld, Germany, in 2006.

Date received: June 29, 2012
Date accepted: January 19, 2014