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Asleep at the automated wheel—Sleepiness and fatigue during highly automated driving

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ABSTRACT

Due to the lack of active involvement in the driving situation and due to monotonous driving environments drivers with automation may be prone to become fatigued faster than manual drivers (e.g. Schömig et al., 2015). However, little is known about the progression of fatigue during automated driving and its effects on the ability to take back manual control after a take-over request. In this driving simulator study with *N*ö=ö60 drivers we used a three factorial 2ö×ö2ö×ö12 mixed design to analyze the progression (12ö×ö5ömin; within subjects) of driver fatigue in drivers with automation compared to manual drivers (between subjects). Driver fatigue was induced as either mainly sleep related or mainly task related fatigue (between subjects). Additionally, we investigated the drivers' reactions to a take-over request in a critical driving scenario to gain insights into the ability of fatigued drivers to regain manual control and situation awareness after automated driving.

Drivers in the automated driving condition exhibited facial indicators of fatigue after 15 to 35ömin of driving. Manual drivers only showed similar indicators of fatigue if they suffered from a lack of sleep and then only after a longer period of driving (approx. 40ömin). Several drivers in the automated condition closed their eyes for extended periods of time. In the driving with automation condition mean automation deactivation times after a take-over request were slower for a certain percentage (about 30%) of the drivers with a lack of sleep (*M*ö=ö3.2; *SD*ö=ö2.1ös) compared to the reaction times after a long drive (*M*ö=ö2.4; *SD*ö=ö0.9ös). Drivers with automation also took longer than manual drivers to first glance at the speed display after a take-over request and were more likely to stay behind a braking lead vehicle instead of overtaking it.

Drivers are unable to stay alert during extended periods of automated driving without non-driving related tasks. Fatigued drivers could pose a serious hazard in complex take-over situations where situation awareness is required to prepare for threats. Driver fatigue monitoring or controllable distraction through non-driving tasks could be necessary to ensure alertness and availability during highly automated driving.

1. Introduction

A driver in a future automated vehicle may be suffering from a lack of sleep or may become fatigued in the course of the drive, just like a manual driver. During automated mode this will not influence driving behavior, as the driver is decoupled from steering, acceleration and braking inputs. However, transitions of control between the driver and the car will always be performed in the context of driver states, such as fatigue or distraction. These transitions of control might be initiated by the driver or they might be initiated by the vehicle. In highly automated driving or conditional automation (i.e. level 3 automation; SAE, 2014; Gasser et al., 2012) certain environmental conditions or road characteristics, such as heavy rainfall or roadwork, will trigger take-over requests if sensor quality degrades and object recognition can no longer be guaranteed.

The levels of vehicle automation as defined by SAE (2014) specify the tasks performed by the automated driving system as well as the responsibilities remaining with the driver during automated driving. The introduction of level 3 automated driving systems is especially critical, as the driver is no longer required to continuously monitor the automation. The driver is free to choose his or her activity during automated driving. The only requirement is that the driver is able to take back manual control over the car if required by the system through a take-over request. However, for the driver it may not be apparent which driver states and driver activities still enable him or her to safely return to manual driving.

Taking the operator of an automated system out of the control loop (Endsley and Kiris, 1995) can result in a decrease in vigilance

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(Parasuraman and Davies, 1977), a loss of situation awareness (Kaber et al., 2006) and mode confusion (Degani et al., 1999). Using highly automated driving functions for extended periods of time may therefore leave the driver in a state where he or she is not immediately able to perform at the same level as a manual driver. It is not yet clear if a take-over can be considered safe if a driver suffers from a lack of sleep or has become fatigued through the monotony of the driving environment and the use of the automation. Will the driver become fatigued during automated driving? And even more importantly: Is the fatigued driver going to be available when the system tells him to be available?

1.1. Prevalence of driver fatigue and fatigue crashes

Looking at manual driving, fatigue in drivers is highly prevalent. Driver fatigue is defined by Williamson et al. (1996) as a state of reduced mental wakefulness, which impairs cognitive and psychomotor performance during driving. According to Brown (1994) the primary causes of driver fatigue during real world driving are irregular and long working hours, which influence the quantity and the quality of sleep, the circadian rhythm and the time-on-task. For the purpose of our study we generalize the term driver fatigue to describe the driver state which occurs as a result of an interaction between passive, task related fatigue due to the monotony, duration and automation of the driving task and sleep related fatigue due to sleep deprivation and time of day. As discussed in Mayand Baldwin (2009), it is possible to differentiate between these sources of driver fatigue using different methods of driver fatigue detection.

In a study by Vanlaar et al. (2008) approximately 15% of the drivers reported to have fallen asleep or nodded off during driving in the course the last year. An analysis carried out for the EU in 2009 estimates that between 10% and 20% of crashes on European roads are directly or indirectly related to driver fatigue (SafetyNet, 2009). Similar values are given by Langwieder et al. (1994), who used in-depth crash analyses to estimate that about 24% of crashes on German highways could be due to fatigued drivers. Internationally, estimates range from 20% to 30% (Camkin, 1990) of crashes due to fatigue, or an increase in crash likelihood by the factor 4 (Dingus et al., 2006), by the factor 5 with less than 5 h of sleep (Stutts et al., 2003), by the factor 8 (Connor et al., 2001) up to a factor of 14 (Cummings et al., 2001).

Accidents with fatigued drivers often happen as a consequence of driving errors, which become more frequent with fatigue and for which fatigued drivers are no longer able to compensate. Steering quality deteriorates (e.g. O'Hanlon and Kelley, 1977; Riemersma et al., 1977) and lane keeping becomes less accurate (e.g. van der Hulst et al., 2001; Åkerstedt et al., 2005). The effects of fatigue are often compared to the effects of alcohol on driving performance: Williamson and Feyer (2000) found that after a period of 17–19 h without sleep psychomotor and cognitive performance had deteriorated as much as in test participants with a blood alcohol content of 0.5 g/l. This is the legally prescribed limit for driving under the influence of alcohol in many countries.

Hence, even one night without sleep or low sleep quality can lead to distinctly measurable cognitive and psychomotor impairments during driving. These impairments can manifest as slower reaction times to emergency situations: Dinges (1995) and Philip et al. (2005) attribute slower reaction times to emergency situations in fatigued drivers to a reduction in vigilance, which impairs the detection of relevant stimuli in the driving environment and is also associated with a general reduction in information processing capacity.

The phenomenon of reduced vigilance in drivers is often discussed as "highway hypnosis" during which drivers pass whole stretches of road without building awareness for the route or surrounding traffic. This state can also develop without a lack of sleep or a long time-on-task, simply from the monotony of a driving task and driving environment. Karrer et al. (2005) call this driver state *Driving Without Awareness (DWA)*, and describe typical symptoms as being unable to recall route sections and experiencing moments of "waking up" during driving. DWA can be detected by trained raters in video recordings of drivers. In these recordings events such as staring eyes without focus, head nodding, rolling eye movements and prolonged eyelid closures are counted and categorized. DWA is associated with an increase in driving errors on several levels of the driving task, as well as a reduction in situation awareness during the drive (Briest et al., 2006).

1.2. Sleepiness, fatigue and loss of vigilance in automated driving

Taking the driver out of the control loop in automated driving systems may further decrease vigilance and increase the risk of becoming fatigued. Some authors suggest that the duration of the drive and the drivers' state may have an influence on the interaction of the driver with the automated driving system (Feldhütter et al., 2016; Merat et al., 2012). Automated driving functions could increase the likelihood of driver fatigue and render the transition from automated driving back to manual driving more difficult (Schömig et al., 2015).

In a driving simulator study, Miller et al. (2015) found that drivers exhibited signs of fatigue after two to three route sections of automated driving, if they had no opportunity to distract themselves through non-driving related tasks. Some authors suggest that this risk may be decreased by allowing the drivers to engage in simple non-driving tasks and by providing them with appropriate feedback about the state of the automation (e.g. Jamson et al., 2013; Miller et al., 2015). The authors discuss that allowing the driver to engage in such activating tasks may have advantages over a fatigued or sleeping driver when rebuilding situation awareness after a take-over request.

In a study by Körber et al. (2015) the authors registered a significant increase in fatigue during an automated drive of 42 min, based on pupil dilation, blink frequency and blink duration. Building on this study, Gonçalves et al., (2016) found that even after only 15 min of automated driving, drivers rated themselves as subjectively tired. Similarly, Feldhütter et al. (2016) found indicators for the development of fatigue during an automated drive of 20 min based on eye-tracking measurements. Fatigued drivers in this study were slower to react to a take-over request, even though this did not seem to influence take-over quality.

Even more critical to safety in automated vehicles are results from a study by Neubauer et al. (2012), which suggests that automated drivers may not only be susceptible to fatigue during long phases of automated driving, but may also be more likely to make use of automated driving functionalities once they have become fatigued. Participants in this study who used the automation performed worse than manual drivers when faced with a critical event.

1.3. Take-over times in automated driving

In conditional automation, a critical event is a take-over request by the automation. The transition to manual driving after a take-over request has by now been studied for a variety of non-driving related tasks (e.g. Gold et al., 2013; Petermann-Stock et al., 2015; Vogelpohl et al., accepted) and in interaction with different designs for human-machine interfaces (e.g. Helldin et al., 2013; Lorenz et al., 2014). The longest take-over times have usually been found for highly distracted drivers who were engaged in a non-driving related task and were therefore completely taken out of the manual control loop (e.g. $M = 5.1$, $SD = 1.9$ s in Vogelpohl et al., accepted; $M = 4.4$, $SD = 0.7$ s in Gold et al., 2013; $M = 3.5$, $SD = 1.2$ s in Melcher et al., 2015; $M = 3.4$, $SD = 1.6$ s in Petermann-Stock et al., 2013).

However, take-over times are often measured as *time to automation deactivation*. Some authors suggest that disengaging the automation after a take-over request may not be the same as a full transition back to manual driving (Gold et al., 2016; Vlakveld, 2015; Vogelpohl et al., accepted). Additional measures of take-over quality and situation awareness after a take-over may be necessary to define safe take-over times associated with high levels of distraction. Eye-tracking measures such as the first glance to the side mirror have been used in some studies (Gold et al., 2013; Lorenz et al., 2014; Radlmayr et al., 2014; Vogelpohl et al., accepted). Other studies have used measures of driving quality (e.g. Merat et al., 2014; Louw et al., 2015) or defined criteria for a successful transition to manual (e.g. Damböck et al., 2012; Strand et al., 2014).

As of yet, there is no single measure approach to define when a transition to manual driving after a phase of automated driving is complete. Similar to automated driving with a distracting non-driving related task, fatigued drivers could be highly removed from the driving task. They could therefore require just as much or even more time than distracted drivers to rebuild situation awareness and to safely disengage the automation in a take-over situation.

1.4. Study aims

To summarize, the duration of an automated drive has been identified as a possible risk factor for the development of driver fatigue during automated driving. Some studies additionally point towards slower or less appropriate reactions to take-over request if the driver has previously become fatigued or towards slower reactions to critical events. Driver fatigue during automated driving might take drivers out of the control loop similar to distraction through non-driving related tasks and may therefore produce similar problems and delays in a take-over situation. These effects could be enhanced if drivers in automated vehicles start their trip being fatigued due to a lack of sleep.

Accordingly, the first aim of this study was to analyze the progression of driver fatigue in drivers who became fatigued (a) mainly due to sleep related fatigue, which was induced by a lack of sleep and the time of day or (b) mainly due to task related fatigue, which was induced by the time on task and the monotony of the driving environment. The second aim of the study was to analyze driver performance in a take-over situation after a take-over request from a state of driver fatigue. Both the progression of fatigue and the performance in a take-over scenario were analyzed for drivers with automation as compared to manual drivers. These analyses will allow a first indication as to whether a transition from a fatigued driver state can be considered safe in the context of driving with high levels of automation.

2. Experimental setup and methods

To analyze the progression of fatigue during highly automated driving and the transition to manual driving from a fatigued driver state we conducted a driving simulator study which comprised the between subject factors *Source of fatigue* and *Automation*, as well as the within subject factor *Time of the rating*. The source of fatigue was defined as either primarily due to a lack of sleep or primarily due to a long monotonous drive without a lack of sleep. Drivers from these two conditions either drove manually or with an activated automated driving system. Additionally, we analyzed the fatigue ratings for the point in time where the rating was given to provide information about the progression of fatigue during the drives. Thus, the experimental plan consisted of four between subject conditions: Lack of sleep + automated driving; long drive + automated driving; lack of sleep + manual driving; long drive + manual driving. Each condition in the experimental plan was randomly assigned to 15 participants. The experimental design and the number of participants assigned to each condition are summarized in Table 1.

Table 1
Experimental design and number of participants in each experimental condition.

Source of fatigue	Automated driving/ Manual driving	Number of participants
Population 1: Lack of sleep + time of day	Manual driving Driving with automation	15 Participants 15 Participants
Population 2: Long monotonous drive	Manual driving Driving with automation	15 Participants 15 Participants

Participants in the condition *Lack of sleep* were instructed during the recruiting process to sleep for a maximum of 5 h in the night before the test drive. Additionally, participants from this sample of drivers were invited into the driving simulator only between 8 p.m. and midnight. This was thought to be representative of driving home late from work after a night with not enough sleep or bad sleep quality.

Participants in the condition *Long drive* were instructed to try to sleep for at least 7 h in the night before the test drive. Participants in this experimental condition were only invited into the driving simulator during daytime (between 9 a.m. and 5 p.m.). Additionally, no participants were invited close to lunch time (between 12 a.m. and 2 p.m.) to avoid possible lows in the circadian rhythm which some studies have found during this time period. This was thought to be representative of using the automated driving system for a longer period of time in otherwise non-detrimental conditions.

The study was conducted in the fixed base, medium fidelity driving simulator at the Technische Universität Braunschweig, Germany. The software used for driving simulation and driving data collection was SILAB (Krueger et al., 2005) in version 5. The driving simulator featured a vehicle mockup and a projection of the driving scene onto three large screens which provided a 180° field of view. Additionally, four small screens were used to simulate rear view mirrors and a speed display. Sound was played back through a surround-sound speaker system (see Fig. 1 for an image of the simulator room and the vehicle mockup).

2.1. Measuring fatigue in automated vehicles

To assess driver fatigue, objective measures such as behavioral and physiological observations should be supplemented by subjective measures such as validated questionnaires (Lal and Craig, 2000). Automated driving disqualifies fatigue measures derived from manual inputs and driving behavior (e.g. Fairclough, 1997; Knipling and Wierwille, 1994; Hartley et al., 2000), as the driver is decoupled from the steering wheel and the pedals. On the other hand, physiological measures such as EEG and ECG (e.g. Lal and Craig, 2001; Lin et al., 2005) can be intrusive and require the driver to be in direct contact with the sensors. Therefore, measures based on the observation of facial, behavioral and eye-based indicators of fatigue seem most suited as objective indicators of fatigue in automated driving.

We trained three raters to search for facial and behavioral indicators of fatigue. The training and the indicators were based on the methods originally proposed by Wierwille and Ellsworth (1994) and expanded by Wiegand et al. (2009). The training included video material from naturalistic driving studies with which the raters learned to identify facial and behavioral indicators associated with different levels of fatigue in drivers. After the trainings sessions the raters were asked to rate 60 s intervals of unknown video material which contained previously identified indicators of fatigue. The ratings were validated against the previously defined indicators and the trainings were repeated until a high fit between the raters was achieved.

During the drives the drivers' faces and upper torsos were recorded by an infrared camera. The camera feed was transmitted to the control room where the trained raters recorded indicators of fatigue and classified the participants' fatigue level based on quality and quantity of the indicators. The indicators for fatigue (e.g. prolonged eyelid closures, yawning and rubbing of the face) were recorded every five minutes for durations of one minute. Based on the indicators recorded in this time period the fatigue level of the drivers was classified on a scale from 0 (awake) to 8 (very strong fatigue). Table 2 lists the indicators of fatigue which the trained raters used to classify the participants in more detail.

To supplement the fatigue ratings made by the trained raters we

Fig. 1. Fixed base driving simulator and vehicle mockup used in the study. Photo by Matthias Powelleit with permission.

provided the participants with an opportunity to rate their own subjectively perceived fatigue. After the drive we asked the participants to give a retrospective estimate of their fatigue directly before the take-over situation using the Karolinska Sleepiness Scale developed by Åkerstedt and Gillberg (1990). These subjective fatigue ratings were obtained outside of the simulator room after driving was finished.

2.2. Take-over scenario

A take-over of control or transition to manual driving was defined as the process of regaining manual control over the car, stabilizing the vehicle and safeguarding the vehicle against potential threats. To analyze the effects of a lack of sleep and long driving on the take-over behavior in drivers after automated driving we introduced one take-over scenario to the course of the drive. Introducing more than one take-over scenario to the drive would have disrupted the progression of fatigue during automated driving as well as manual driving. Therefore, each participant in the study experienced only one take-over situation which also marked the end of the experiment.

Before the take-over situation the participants in our study were driving on a simulated three-lane highway with a traffic density of approx. 15 cars passing on the middle lane every minute and a lower traffic density on the right lane, which afforded overtaking maneuvers approx. once every two minutes. The three lanes going into the opposite direction were separated by double guard rails and there was also some infrequent traffic on these lanes. The landscape surrounding the highway included trees and fields close to the highway, some hills/valleys and houses in the middle distance and mountains further in the distance. Weather conditions were clear with some clouds. An example of the simulated environment can also be seen from the background in Fig. 1.

In the *Lack of sleep* condition the take-over scenario was triggered by the trained fatigue raters as soon as the driver had been classified as level 3 (*medium fatigue,* indicated among others by prolonged eyelid closures, glassy eyes with long blinking pauses or stretching/lolling) or above, but after a minimum driving time of 15 min. In the experimental condition *Long drive* the take-over request was triggered after approximately one hour of driving.

For the drivers with the automated driving system the take-over request was indicated by a distinct auditory warning signal and a symbol overlaid on the projection screen. To assure comparable reactions from the manual drivers this group received the same warning signal at the point where the drivers with automation were issued the take-over request. As a rationale for the participants, we explained to the manual drivers before the start of the experiment that their vehicle had a warning system which would notify them beforehand if an unusual and potentially dangerous driving situation lay on the road ahead.

As a take-over scenario we specified a situation in which the cars' sensor quality is degraded due to a heavy rainfall and a take-over

Table 2
Levels of fatigue and indicators of fatigue used by the trained raters for classification.

Fatigue Level	Facial and behavioral indicators of fatigue
0 – awake	Fast eyelid closure, inconspicuous blink behavior, continuous switches of focus, upright sitting position, fast saccades, hand position on steering wheel" 10 and 2"
1 – light fatigue (−)	Prolonged eyelid closures of up to 0.5 s, tired facial expression, yawning, rubbing/scratching of face, grimacing, tilted head
2 – light fatigue (+)	
3 – medium fatigue (−)	Prolonged eyelid closures (approx. 0.5–1 s), eyes staring/"glassy eyes "with long blinking pauses (> 3 s), stretching/lolling, eyes half closed
4 – medium fatigue (0)	
5 – medium fatigue (+)	
6 – strong fatigue (−)	Very long eyelid closures (1–2 s), eye rolling, head-nodding
7 – strong fatigue (+)	
8 – very strong fatigue	Eyelid closures > 2 s, micro-sleep episodes, startling awake from sleep or micro-sleep

Note: The nuances of fatigue (+/0/−) were determined through the number of occurrences of the indicators in the one minute rating interval for each fatigue level.

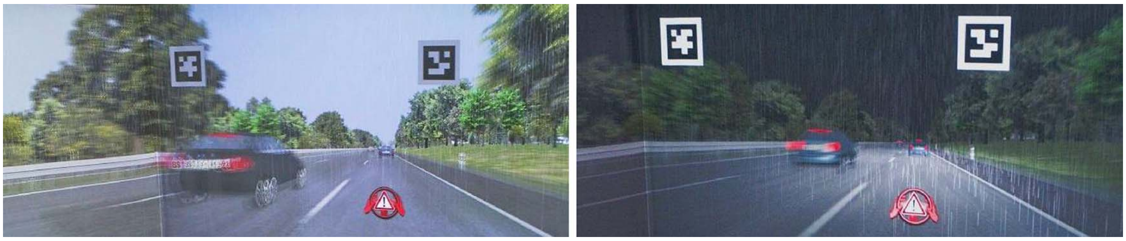

Fig. 2. Take-over scenario in the condition *Long drive* (left) and *Lack of sleep* (right).

request is issued because the system can no longer guarantee reliable detection of lane markings and objects. The beginning of the rainfall triggered the take-over request for the drivers with automation and the warning signal for the manual drivers. In this situation a lead vehicle was simulated which matched the speed of the ego car. In the left lane passing cars were simulated with a high traffic density of approximately 25 passing cars every minute. Fig. 2 shows the view the drivers had in the take-over scenario for the conditions *Long drive* and *Lack of sleep*. The lighting conditions reflected the time of day during which the experiment was conducted: Daytime driving for the *Long drive* condition and nighttime driving for the *Lack of sleep* condition.

After the take-over request we expected most of the drivers with the automated driving system to take back manual control in a time frame approximately comparable to the mean automation deactivation times found in highly distracted driving with automation (i.e. around 3–5 s; Gold et al., 2013; Melcher et al., 2015; Petermann-Stock et al., 2013; Vogelpohl et al., accepted). To be able to assess the drivers reactions to an unexpected event after a take-over request we implemented a braking lead vehicle in the scenario after most drivers should have taken back manual control and deactivated the automation (at 175 ms after the take-over request or approximately 5.25 s at an assumed constant speed of 120 km/h). The lead vehicle decelerated from a speed of 120 km/h to 80 km/h, similar to a driver trying to adapt to the bad weather conditions. After the lead vehicle had started braking the drivers in the ego vehicle had an additional 4.75 s to react to the new speed of the lead vehicle (i.e. to either change lanes or reduce the speed), adding up to an overall reaction time budget after a take-over request of 10 s (cf. Fig. 3). If the driver had not disengaged the automation during these 10 s the automation would transition the car to a simple form of minimal risk/safe state (e.g. Reschka and Maurer, 2015) by coming to a complete stop.

2.3. Setup of the automated driving condition

We set up the automated driving system in the driving simulator to reflect the current proposals for a level 3 (SAE, 2014) conditional or highly automated (Gasser et al., 2012) driving system. The system was therefore able to safely follow the course of the road and to keep a distance to vehicles in front. It was also able to reliably determine the position of other vehicles on the road.

The automation was set to a speed of 120 km/h, but also adhered to lower speed limits (100 km/h) which were frequently posted alongside the simulated road. Additionally, the automated driving system

Table 3
States and Symbols of the automated driving system implemented in the simulator.

Available	Active and safe	Active but requesting to take-over
		
The automation is ready to take over control of the vehicle (steering, acceleration, braking).	The automation is active and monitoring the environment. The automated steering and braking functions are engaged.	The automation has detected a situation which requires an intervention by the driver. Please take over the control of the vehicle.

performed overtaking maneuvers if a lead vehicle drove at a lower speed and if the left lane was free of passing cars. Overtaking maneuvers as well as speed limits which required the system to adapt driving behavior were frequent during the course of the drive.

The implemented system neither gave out false warnings nor did it miss critical situations. It provided constant feedback about the state of the automation. This feedback was provided through a simulated head-up display projected onto the road in front of the driver. Automation modes were *Available*, *Active and safe* or *Active but requesting to take-over* as illustrated in Table 3.

2.4. Instructions about the automated driving system

All participants in the study were provided with an opportunity to familiarize themselves with the driving simulator and the automated driving system before the start of the experiment. The training session took approximately 15 min during which the participants experienced manual driving (approx. 5 min), highly automated driving (approx. 5 min) as well as a take-over request and a return to manual driving.

Before the training drive participants were instructed about the capabilities of the automated driving system as described in the setup of the automated driving condition. They were told that the system would issue a take-over request with a sufficient time buffer if the system could no longer guarantee safe automated driving. The participants were told that the automation would stay activated as long as they did not disengage the system, even after a take-over request. Deactivation

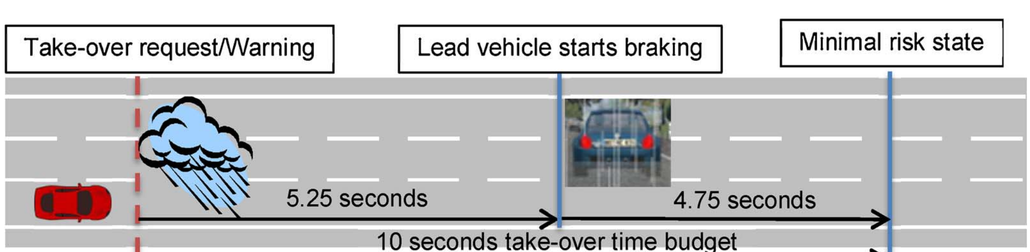

Fig. 3. Time budgets in the take-over scenario.

Table 4
Reaction times and reaction time definitions for the study.

Reaction time to…	Standardized end point of reaction time measurement
Eyes on Road	Eye focus on street center (derived from eye tracking measurements)
Hands On	At least one hand completely grasps the steering wheel (derived from video recordings)
Feet On	The right foot touches the accelerator or the braking pedal, or the right foot hovers immediately above the brake pedal (derived from video recordings)
Automation Off	The automation has been deactivated through either the brake pedal or a switch behind the steering wheel (derived from simulator driving data)
Brake Reaction	The brake pedal is depressed by at least 10% of its maximum travel after the lead vehicle has started braking (derived from simulator data)
Gaze Side Mirror	The first gaze to the left side mirror after the take-over request/warning
Gaze Speed	The first gaze to the speedometer after the take-over request/warning

of the automated driving system could either be carried out using a lever behind the steering wheel (similar to a cruise control lever) or by pressing the brake pedal.

2.5. Measuring reaction times and situation awareness in the take-over scenario

To measure reaction times and situation awareness in the take-over scenario we defined start and end points for reaction time measurements which could be compared for the factors *Source of fatigue (Long drive, Lack of sleep)* as well as *Automation (automated driving, manual driving)*. Reaction time measurements were chosen to reflect both immediate reactions to the take-over request (eyes focus back on the road, hands and feet return to the steering wheel/pedals, automation is deactivated) as well as more long term preparatory reactions and reactions to the braking lead vehicle such as braking and/or steering, looking at the side mirror and looking at the speed display.

As a starting point for all reaction time measurements we used the point in time where the take-over request was issued to the drivers in the automated driving condition and where the manual drivers were issued a warning signal. Table 4 provides an overview of the reaction times measured in this study and defines the end points for each measurement. Reaction time measurements were derived either from eye-tracking data (recorded with a Dikablis 2.5 eye-tracking system; Lange, 2005), video recordings with a frame rate of 25 frames per second or simulator data. The Dikablis system is a head-mounted eye-tracking system which fuses video data from an infrared eye-camera with video data from a front-facing camera and thereby enables reliable eye-tracking, even if the head is moved during driving.

For the purpose of this study we defined situation awareness as the time taken to look at the side mirror and at the speed display for the first time after the take-over request/warning signal. Additionally, we analyzed the type of reaction to the braking lead vehicle (braking and staying in the lane vs. steering and overtaking). While these are certainly not the only measures of situation awareness possible in such a situation it allows a first prediction as to whether a driver has begun to perceive and understand the traffic situation around him or her and the position and speed of the car in relation to this situation (cf. Damböck, 2013). Additionally, the reaction time to the braking lead vehicle was thought to represent a basic measure of situation awareness, as it required the driver to perceive the vehicle, understand the significance of the brake lights and to choose to either brake or change lanes after a prediction of the lead vehicles future path.

2.6. Study participants

N = 60 participants with an age between 18 and 87 (M = 41.3, SD = 21.1) years took part in the driving simulator study. Younger drivers between the ages of 18–35 represented about half of the participants (48%), while older age groups made up the other half of the participants (36–55 years, 25%; 55+ years, 27%). Older participants were tested for their ability to drive during a training drive and recruited from a pool of participants who were known to be active drivers. 38 participants in the study were male (63%), 22 participants were female (37%). Participants received either monetary compensation or course credit for taking part in the study. Prior to the beginning of the study we obtained informed consent about data use and video recording from the participants and told them that they were free to drop out of the study at any point without any disadvantages and without loss of their monetary compensation.

Approximately 75% of the participants reported some prior experience with driving assistance systems which took over part of the driving task (i.e. Cruise Control, ACC, Lane keeping assistance, etc.). About half of the participants had taken part in a driving simulator study before, but none had taken part in a simulator study about automated driving. The participants reported a wide range of driving experience ranging from less than 3000 km per year to more than 50.000 km per year. The distribution of driving experience in the study is summarized in Fig. 4 (left). Additionally, participants were asked before the study to rate their subjective knowledge about automated driving on a scale from very low to very high. Fig. 4 (right) visualizes the distribution of these subjective ratings.

Before taking part in the study we asked the participants to report the times they went to sleep the night before and woke up in the morning. We encouraged participants to give realistic times and clarified that they would still receive their compensation if they had not adhered to the assigned sleep schedules (maximum of 5 h sleep in the condition *Lack of sleep*, minimum of 7 h of sleep in the condition *Long drive*). The mean sleep duration in the *Lack of sleep* condition was reported as M = 4 h and 52 min, the condition *Long drive* reported an average of M = 7 h and 52 min of sleep.

Some drivers in the *Long drive* condition with/without automation

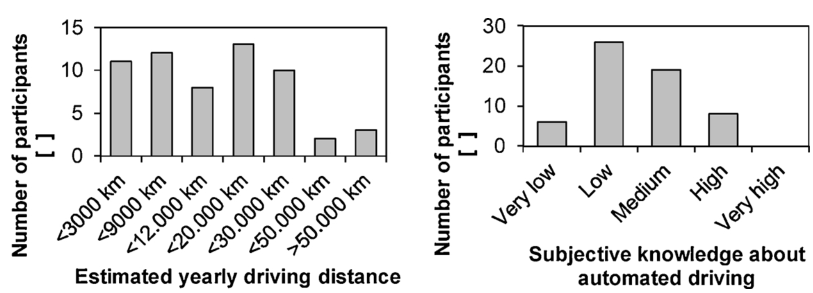

Fig. 4. Driving experience (left) and subjective knowledge about automated driving (right) in the sample of participants.

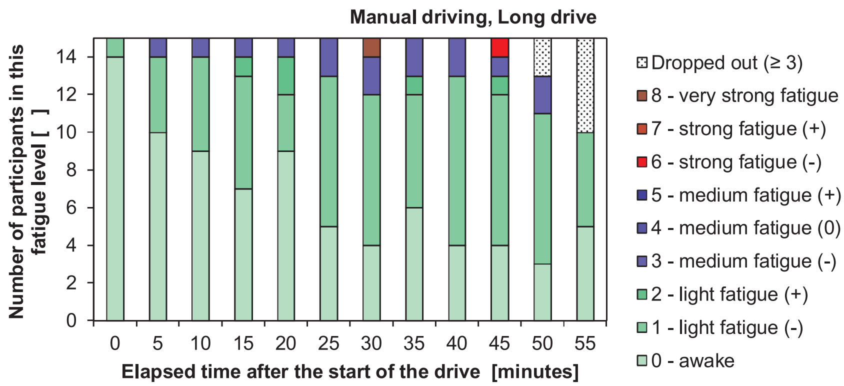

Fig. 5. Progression of fatigue ratings for the manual driving condition in the condition Long drive.

showed signs of simulator sickness after driving for a longer period of time. If simulator sickness occurred prior to 40 min of driving time the participants were excluded from the sample. If minor indicators of simulator sickness occurred only after at least 40 min of driving the take-over scenario was triggered and participants continued driving until the end of the scenario, but not for the full 60 min. $N = 2$ participants in the *Long drive, automated driving* condition and $n = 5$ participants in the *Long drive, manual driving* condition received early take-over requests (< 45 min). For these participants no fatigue ratings for the remaining time to the full hour could be recorded, but reaction time data for the take-over requests was obtained.

2.7. Data treatment and statistical analysis

As the duration of the experiment in the fatigue group depended on when the target fatigue level was reached, in a first step of the analysis the frequency of fatigue levels over time (maximum 12 time-points) was analyzed in both manual driving and driving with automation in both fatigue conditions (*Lack of sleep* vs. *Long drive*). As the number of time-points available varied strongly, it was not possible to include the factor *Time of rating* in the further analyses. Instead, the fatigue level directly before the take-over request was examined with a two-way ANOVA including the factors *Automation* (manual vs. automated) and *Source of fatigue* (Lack of sleep vs. Long drive). This was also done for the subjective rating of fatigue directly before the take-over request.

With regard to the reactions to the take-over request, this could only be analyzed for the drivers with automation comparing the two groups fatigue vs. time-on-task using a *t*-test for independent groups (time to hands on, feet on, first glance on the road and automation deactivation time).

In order to examine the behavior after the transition to manual control, two-way ANOVAs including the comparison of manual drivers vs. drivers with automation (factor 1) and *Lack of sleep* vs. *Long drive* (factor 2) were computed for the first glance to the side mirror and the first glance to the speed display. Finally, the reactions to a braking lead vehicle were examined. In the first step, the frequency of different reactions (braking vs. steering) was compared between the four groups. As the reactions were substantially different in the manual driving conditions compared to the automated driving conditions, a comparison of brake reaction time was only possible for the two automated driving groups *Lack of sleep* and *Long drive*, which were compared using *t*-tests. The level of significance for all tests was set at $\alpha = 0.05$.

3. Results

The results describe the fatigue ratings given by the trained raters and by the drivers themselves. We present the immediate reactions of the fatigued drivers to the take-over request/warning signal, as well as measures of situation awareness after the transition to manual for the driver with an automated driving system compared to the manual drivers.

3.1. Progression of fatigue

The progression of fatigue was analyzed separately for the experimental conditions *Lack of sleep* and *Long drive*. Drivers in the *Long Drive* condition continued driving until the full planned duration of one hour was reached. In contrast, in the *Lack of sleep* condition the experimental drive was interrupted by a take-over request/warning signal as soon as the participants had been classified at least as *medium fatigued*, but only after a minimum driving duration of 15 min. Therefore, some participants in this condition reached higher levels of fatigue before the take-over request was issued. All participants ended the drive after the take-over request/warning signal.

To facilitate the interpretation of the data we first provide visualizations for the number of participants in each level of fatigue over the progression of experiment. The graphs show the number of participants in each fatigue level as categorized by the raters at every rating interval from the start of the drive to the end of the drive, which also visualizes the effect of the *Time of the rating* on the level of fatigue. Figs. 5 and 6 show the distribution of fatigue levels in the *Long drive* condition. Figs. 7 and 8 give the same comparison for the *Lack of sleep* groups. The graphical analysis of the data based on Figs. 5–8 shows (a) a general increase in fatigue over the course of the drive (b) a faster increase in fatigue for the drivers with automation compared to the manual drivers, (c) a faster increase in fatigue for the drivers with a previous lack of sleep compared to the long drive and (d) an possible interaction between a previous lack of sleep and automated driving which leads to high levels of fatigue early after the start of the drive.

Due to the high number of drop-outs in the fatigue ratings we chose to perform statistical analyses for the fatigue ratings only for the ratings points for which all data points were available. This meant that statistical analysis for the *Long drive* condition was carried out for 9 rating points (up to 40 min) and statistical analysis for the *Lack of sleep* condition was carried out for 4 rating points (up to 15 min).

In a repeated measures ANOVA of the fatigue ratings for the condition *Long drive* we found a significant interaction between the factors *Time of the rating* and *Automation* ($F(8,224) = 4.09$, $p < .01$, $\eta_p^2 = 0.13$). Additionally, there were significant main effects for both factors (*Time of the rating* $F(8,224) = 10.68$, $p < .01$, $\eta_p^2 = 0.28$; *Automation* $F(1,28) = 7.43$, $p = .01$, $\eta_p^2 = 0.21$). The means of the fatigue ratings of the drivers with automation and the manual drivers in the condition *Long drive* are shown in Fig. 9 over time. While there is only a very small increase in fatigue in the manual group, there is a clear increase in the automated driving group up to a rating of about 4 ("Medium fatigue") after 40 min of driving.

Examining the fatigue ratings in the condition *Lack of sleep* there was also a significant interaction between the factors *Time of the rating*

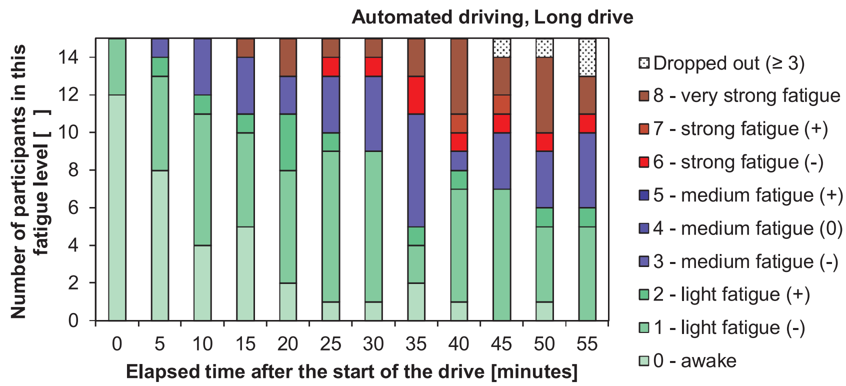

Fig. 6. Progression of fatigue ratings for the automated driving condition in the condition Long drive.

and *Automation* ($F(3,84) = 3.39$, $p = .02$, $\eta_p^2 = 0.11$) and a significant main effects for the factor *Time of the rating* $F(3,84) = 8.86$, $p < .01$, $\eta_p^2 = 0.24$. No significant main effect was found for *Automation* ($F(1,28) = 2.23$, $p = .15$, $\eta_p^2 = 0.07$). Fig. 10 shows the results. In this condition, drivers in the automated driving group reached a level of about 3 after 15 min. In the manual driving group, the increase was much slower. As indicated above, these fatigue ratings only include the ratings up to the point were no take-over requests had yet been issued and fatigue ratings of all drivers could be used. The further progression of fatigue in this experimental condition can be seen from Figs. 7 and 8. Table 5 additionally provides the means and standard deviations of the fatigue ratings for each of the four experimental conditions in the study for each rating time included in the statistical analysis.

3.2. Fatigue at the take-over request

In the experimental condition *Lack of sleep* the raters triggered the take-over request as soon as the drivers exhibited facial and behavioral indicators attributed to a medium level of fatigue (level 3) and the participant had been driving for at least 15 min. For the last rating before the take-over request analysis revealed a significant effect for both variables (*Source of fatigue*: $F(1,56) = 9.01$, $p < .01$, $\eta_p^2 = 0.14$; *Automation*: $F(1,56) = 15.03$, $p < .01$, $\eta_p^2 = 0.21$). As Fig. 11 shows, mean fatigue ratings were higher after automated driving as compared to manual driving. Moreover, drivers with a lack of sleep had a higher fatigue rating than drivers after a long trip. The highest fatigue ratings were thus reached in drivers with a lack of sleep who were using the automation.

In addition to the fatigue ratings by the trained raters we asked the drivers to rate their subjective fatigue before the take-over situation on the Karolinska Sleepiness Scale (Åkerstedt and Gillberg, 1990). In the ANOVA of the subjective fatigue ratings conditions *Automation* and *Source of fatigue* we found significant effects for the source of fatigue (lack of sleep vs. long drive; $F(1,56) = 4.52$, $p < .01$, $\eta_p^2 = 0.08$) and for the presence of automation (manual driving vs. automated driving; $F(1,56) = 8.40$, $p < .01$, $\eta_p^2 = 0.13$).

The subjective fatigue ratings of the participants before the take-over are visualized for the drivers after a long drive/with a lack of sleep and after automated/manual driving in Fig. 12. The subjective ratings for the fatigue before the take-over were highly correlated with the last ratings before the take-over given by the trained raters (correlation 0.53, $p < .01$).

3.3. Immediate reactions to the take-over request

Reaction times after a take-over request were recorded to provide indications for the time needed to regain manual control over the vehicle from a fatigued state after automated driving.

Manual drivers' hands on/feet on-reactions after the warning signal were not included in this analysis, because all manual drivers already had their hands on the steering wheel and their feet on the pedals at the moment the warning was issued. We found no significant differences between drivers with a *Lack of sleep* and the *Long drive* for the times needed to perform the manual operations *Hands on* ($F(1,25) = 0.78$, $p = .39$, $\eta_p^2 = 0.03$) and *Feet on* ($F(1,25) = 0.17$, $p = .68$, $\eta_p^2 = 0.01$). Overall, drivers with automation had their hands back on the steering wheel after $M = 1.7$ ($SD = 0.7$) s and their feet on the pedals after $M = 2.8$ ($SD = 1.4$) s. However, some participants took up to 4.3 s (*Hands on)*, respectively 6.3 s (*Feet on)* to perform these reactions after the take-over request (cf. Fig. 13).

Regarding the first glance to the road, we found no significant interaction in the two-factorial analysis of the effects of automation and the source of fatigue ($F(1,51) = 0.13$, $p = .73$, $\eta_p^2 = 0.00$). There was a significant main effect for *Automation* ($F(1,51) = 6.20$, $p = .02$, $\eta_p^2 = 0.11$), but no main effect for *Source of fatigue* ($F(1,51) = 0.02$, $p = .90$, $\eta_p^2 = 0.00$). Almost all manual drivers had their eyes on the

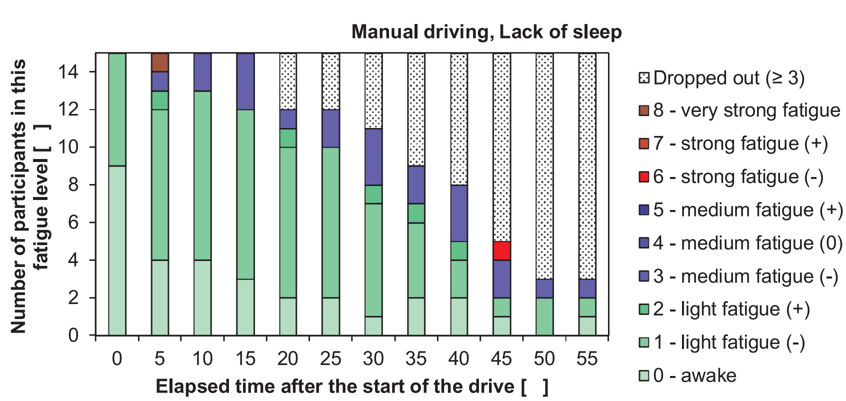

Fig. 7. Progression of fatigue ratings for the manual driving condition with a lack of sleep over the course of the drive.

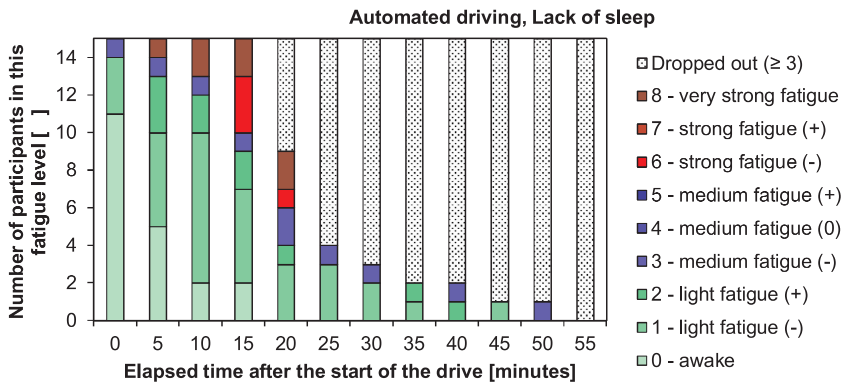

Fig. 8. Progression of fatigue ratings for the automated driving condition with a lack of sleep over the course of the drive.

road at the moment the warning was issued ($M = 0.0$, $SD = 0.1$ s). Some drivers with automation did not look at the road during driving, resulting in a higher mean reaction time of $M = 0.2$ ($SD = 0.4$) s.

The automation was deactivated by the drivers by either pulling a lever behind the steering wheel or by using the brake pedal. Drivers deactivated the automation $M = 2.9$ ($SD = 1.7$) s after the take-over request was issued. An ANOVA for the group differences between the drivers with a lack of sleep ($M = 3.6$, $SD = 2.2$ s) and the drivers after a long drive ($M = 2.5$, $SD = 1.0$ s) showed no significant difference between these conditions ($F(1,25) = 1.30$, $p = .26$, $\eta_p^2 = 0.05$). However, three participants from the lack of sleep condition exhibited very long reaction times of 7.7, 6.9 and 5.5 s.

From the visualization of the automation-off times (cf. Fig. 14) it is apparent that about 30% ($n = 4$) of the drivers in the lack of sleep condition seem to have taken considerably longer to deactivate the automation compared to the long drive condition. Post-hoc analysis of the drivers who had taken more time to deactivate the automation revealed that of the $n = 4$ participants with reaction times > 5 s, $n = 3$ participants' state had been classified as *very strong fatigue.* Additional video analysis showed that during the minute before the take-over request these participants exhibited strong signs of fatigue with prolonged eyelid closures and strong behavioral indicators of fatigue (eye-rolling, eyes half-closed). Interestingly however, all of these participants had their eyes open and directed at the road before the acoustic warning signal/take-over request was issued.

3.4. Measures of awareness for the take-over situation

As measures for the awareness of the situation after the take-over request/warning signal, we analyzed the first glances to the side mirror and to the speed display, as well as the drivers' braking and steering reactions to the onset of the braking lead vehicle. The lead vehicle started braking as soon as the ego vehicle had passed a trigger point at 175 m behind the take-over request/warning signal. Depending on the ego vehicles' speed, this corresponded to a time of approximately 5 s after the take-over request.

In a two-factorial ANOVA with the factors *Automation* and *Source of fatigue* we found no statistically significant differences or interactions between the experimental conditions in the time to the first glance to the side mirror (all F values < 1.00, all p values $> .32$). On average, drivers with automation took $M = 12.2$ ($SD = 6.2$) s to first look at the side mirror after a take-over request compared to manual drivers ($M = 10.4$, $SD = 5.0$ s). Participants in the automated driving condition which also suffered from a lack of sleep took $M = 13.8$, $SD = 5.0$ s to first glance at the side mirror.

Regarding the first glance to the speed display, in a two-factorial ANOVA we found no interaction between the variables ($F(1,50) = 0.06$, $p = .81$, $\eta_p^2 = 0.00$) and a significant main effect of *Automation* ($F(1, 50) = 9.01$, $p < .01$, $\eta_p^2 = 0.15$) with slower average reaction times for the drivers with automation ($M = 6.3$, $SD = 4.7$ s) compared to the manual drivers ($M = 3.4$, $SD = 1.9$ s). We found no effect of the *Source of fatigue* on the time to the first glance to the speed display ($F(150) = 0.62$, $p = .44$, $\eta_p^2 = 0.01$). The differences in the reactions between the drivers with automation and the manual drivers for the first glance to the speed display are visualized in Fig. 15.

As an additional measure of awareness for the traffic situation we analyzed the drivers' reactions to a braking lead vehicle. We measured brake reaction times and additionally classified the reactions as either braking or as a lane change without braking.

We found no statistically significant differences in the braking/steering behavior between the *Lack of sleep* (Mean rank = 31) and the *Long drive* (Mean rank = 30) conditions ($U = 435.00$, $p = .79$, $r = 0.03$). However, a test of the braking/steering behavior between the *automated driving* (Mean rank = 23) and the *Manual driving* (Mean rank = 38) conditions showed an effect of automation on the steering behavior after the take-over request ($U = 225.00$, $p < .01$, $r = 0.52$). Only 10% of the drivers with automation chose to switch lanes after the brake lights had become visible. In contrast, 60% of the manual drivers switched lanes without braking to overtake the slower lead vehicle. The differences in braking and steering behavior for the experimental conditions are additionally visualized in Fig. 16.

Because of the small sample size for braking in the manual driving conditions it was not possible to compare brake reaction times between the automated and the manual driving conditions. However, we

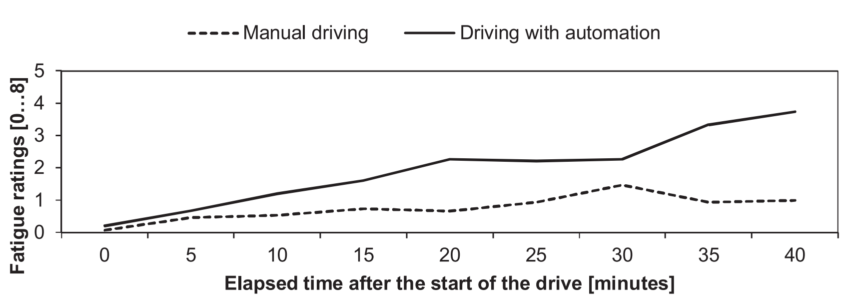

Fig. 9. Means of the fatigue ratings over the duration of the experiment in the condition *Long drive.*

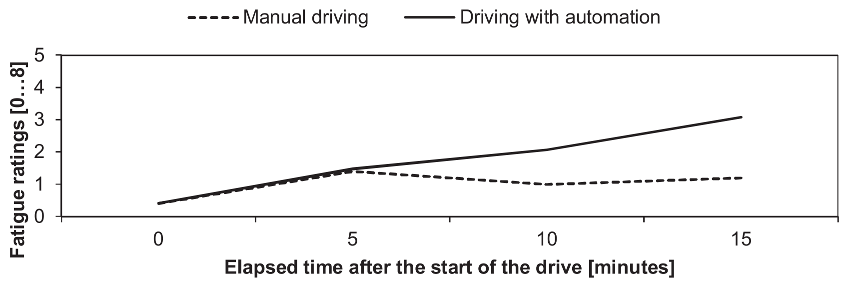

Fig. 10. Means of the fatigue ratings over the duration of the experiment in the condition *Lack of sleep*.

Table 5
Means of fatigue ratings for each experimental condition by duration of the drive.

Condition	Mean fatigue ratings by trained raters after … minutes of the drive											
	0	5	10	15	20	25	30	35	40	45	50	55
Automated Driving + Lack of sleep	0.4 (0.8)	1.5 (2.0)	2.1 (2.5)	3.1 (2.9)	–	–	–	–	–	–	–	–
Automated Driving + Long drive	0.2 (0.4)	0.7 (0.9)	1.2 (1.1)	1.6 (2.1)	2.3 (2.5)	2.2 (2.2)	2.3 (2.2)	3.3 (2.6)	3.7 (3.3)	–	–	–
Manual Driving + Lack of sleep	0.4 (0.2)	1.4 (0.5)	1.0 (0.5)	1.2 (0.3)	–	–	–	–	–	–	–	–
Manual Driving + Long drive	0.1 (0.3)	0.5 (0.8)	0.5 (0.8)	0.7 (0.9)	0.7 (1.0)	0.9 (1.0)	1.5 (2.0)	0.9 (1.0)	1.0 (0.9)	–	–	–

Note: For all experimental conditions only the means for which the full number of participants (n = 15) was available are reported. Dashes indicate rating times with n < 15. Values in brackets signify standard deviations.

analyzed brake reaction times for the two automated driving conditions (*Lack of sleep* vs *Long drive;* $F(1,25) = 2.78$, $p = .11$, $\eta_p^2 = 0.10$). Here, we found no statistically significant differences between these conditions, but a tendency for slower brake reaction times after driving with a lack of sleep. Mean brake reaction times in the lack of sleep condition were $M = 2.8$ ($SD = 1.0$) s, compared to $M = 2.3$ ($SD = 0.6$) s in the long drive condition (cf. Fig. 17).

4. Discussion and implications for system design

We investigated the progression of fatigue in drivers with automation as compared to manual drivers during (a) driving with a lack of sleep and (b) driving for long periods of time. To gain insights into the ability of drivers to handle take-over requests and subsequent critical traffic situations we additionally analyzed these drivers' reactions to a take-over request in adverse weather conditions and the reactions to a braking lead vehicle shortly after the take-over.

Our results point towards a faster and more extreme progression of fatigue for drivers in automated vehicles. Drivers in automated vehicles will likely be especially prone to fatigue in the presence of a previously acquired lack of sleep, even more so than manual drivers. Drivers with automation in our study were generally able to take back manual control of the car, even after micro-sleep episodes. However, some drivers took longer to deactivate the automation and exhibited gaze behavior and driving behavior different from the manual drivers. Drivers with automation needed longer to check their speed on a speed display after a take-over request. Additionally, after a take-over request/warning signal the automated drivers more frequently chose to brake and stay in the lane behind a braking lead vehicle, compared to the manual drivers who often overtook the braking lead vehicle without braking.

4.1. Fatigue will be frequent in automated driving

Fatigue in drivers in automated vehicles will most likely be impossible to avoid. Drivers may suffer from a lack of sleep at the start of the drive and the results from our study indicate that automated driving is unlikely to improve the fatigued state if the driver is not allowed to use the automated driving period for rest or sleep.

In this study, the presence of automation led to generally higher levels of fatigue in the automated driving condition compared to manual driving, which were also exhibited earlier in the course of the drive. Already after 20 min about half of the participants in the automated driving condition had reached a medium level of fatigue or higher. If we searched for that same ratio of fatigued drivers in the manual driving condition we only had a comparable number of fatigued drivers after 45–50 min of driving. It appears that driving with automation for as little as 15–20 min can lead to serious driver fatigue, if no countermeasures against the development of fatigue are provided (cf. Gonçalves et al., 2016; Feldhütter et al., 2016).

The interaction between the presence of automation and a previous lack of sleep indicates that while there was a general increase in fatigue in the drivers during the course of the drive, this increase was stronger for the drivers with automation and especially pronounced for the drivers with automation and with a lack of sleep. Manual drivers with a lack of sleep also showed signs of becoming fatigued over the course of

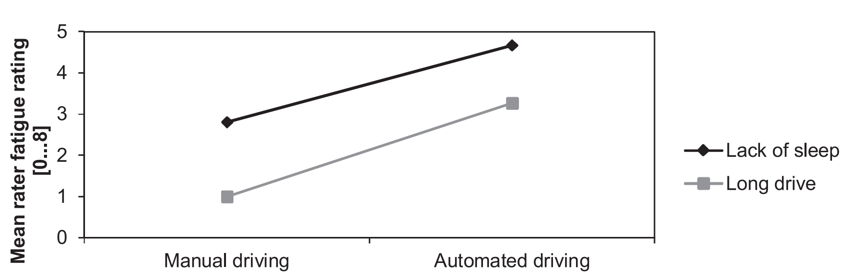

Fig. 11. Means of the last rating before the take-over request/warning signal.

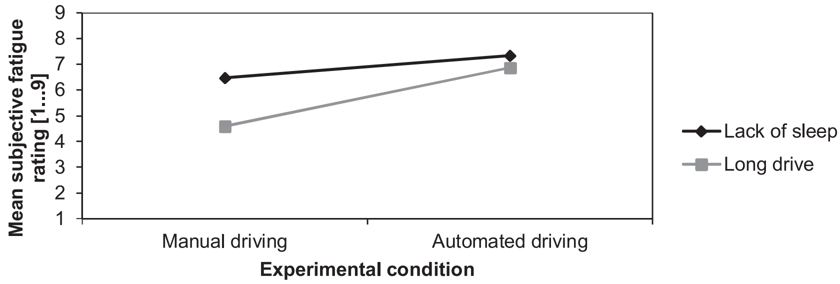

Fig. 12. Mean subjective fatigue ratings of the drivers on the Karolinska Sleepiness Scale before the take-over request.

the drive. However, manual drivers became fatigued later and fatigue levels were less extreme. It is especially concerning, that in our study the drivers with automation who had slept enough during the previous night frequently exhibited indicators of fatigue during the course of a one hour drive. In the comparable manual driving condition similar signs of fatigue were only very rarely found.

By analyzing the progressions of fatigue in the different experimental conditions we can also gather first information about a length of automated driving time during which we would expect fatigue to occur. Manual drivers with a sufficient amount of sleep showed almost no signs of fatigue during the course of one hour of simulated driving in a monotonous environment. For the drivers in the automated driving condition with a sufficient amount of sleep we found indicators for medium to high fatigue in half the participants after approx. 30–35 min. Looking at the progression of fatigue for the drivers with a lack of sleep, half of the participants in the manual driving condition exhibited indicators of fatigue after approx. 35 min. For the drivers with automation in the lightly sleep deprived conditions we found a comparable ratio of participants after approx. 20 min.

If we only look at the last rating that was given by the trained raters before the take-over request was issued, we can also see a difference between the automated driving groups and the manual driving groups. Basically, manual drivers got tired, if they were tired to start with (due to a lack of sleep and the time of day). However, drivers with automation showed indicators of fatigue regardless of the source of the fatigue: Lack of sleep and time on task had very similar and very strong effects on the fatigue levels for this experimental group.

However, the fatigue measured by our trained raters could actually be two different kinds of fatigue. The long drives with automation may primarily have induced task related, passive fatigue (Desmond and Hancock, 2001), characterized by a loss of task engagement. This fatigue was then reduced by interrupting the monotonous task of *not driving*. In contrast, the lack of sleep groups primarily suffered from sleep related fatigue, due to sleep loss and the time of day. This fatigue was only slightly reduced by the return to manual driving and persisted after the take-over. This is in accordance with the model for driver fatigue proposed in May and Baldwin (2009).

These hypotheses are also well in agreement with the findings in Karrer et al. (2005) and Briest et al. (2006), who also found many of the facial and behavioral indicators of fatigue used in this study during long monotonous drives without a previous lack of sleep. The authors discuss this driver state as *Driving Without Awareness (DWA)*, during which drivers develop a reduced situation awareness. *DWA* may therefore also be a good approximation of the drivers' state during longer phases of automated driving.

4.2. Fatigued drivers can be slow to react to take-over requests

In many cases, when a transition back to manual driving is required, the driver therefore will not be at a peak performance level, but may be fatigued through long driving durations and/or a lack of sleep. This could negatively influence reaction speed and reaction quality in a take-over situation.

Concerning the speed of the take-over from a fatigued state we found no increase in the time it took the drivers to physically take back manual control, i.e. to grasp the steering wheel and to return their feet to the pedals. However, we observed that 30% (n = 4) of the drivers with a lack of sleep took considerably longer (approx. 5–8 s) to deactivate the automation. In a previous study where we employed the same take-over scenario and drivers received a take-over request after a short automated drive (approx. 5 min, Vogelpohl et al., accepted), the distribution of the reaction times to a take-over request was very similar to that of the group of drivers in the long drive condition, but not to that of the group of drivers with a lack of sleep.

The distribution of reactions in the condition with a lack of sleep differed considerably from these experimental conditions. In fact, if we look at the point in time where 90% of the drivers in the lack of sleep condition had deactivated the automation, this reaction time was very similar to the drivers in our previous study who were highly distracted by a motivation non-driving related task (7–8 s, Vogelpohl et al., accepted) and are also comparable to automation deactivation times which have been found for drivers performing non-driving related tasks

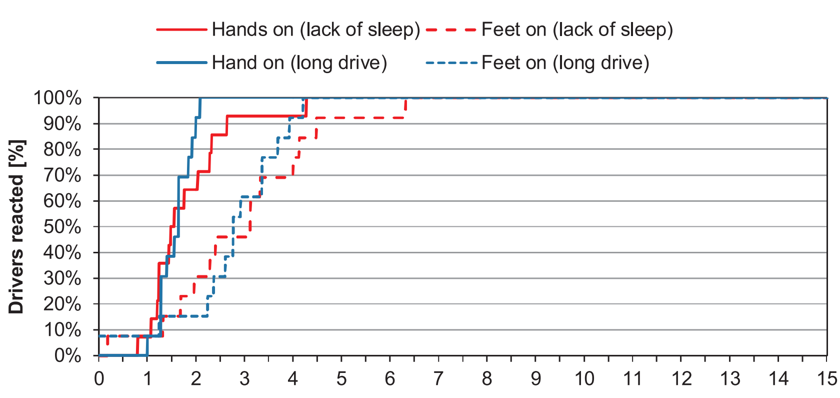

Fig. 13. Cumulative percentages of drivers who had reacted to the take-over request by grasping the steering wheel (solid lines) and put their feet back on the pedals (dashed lines).

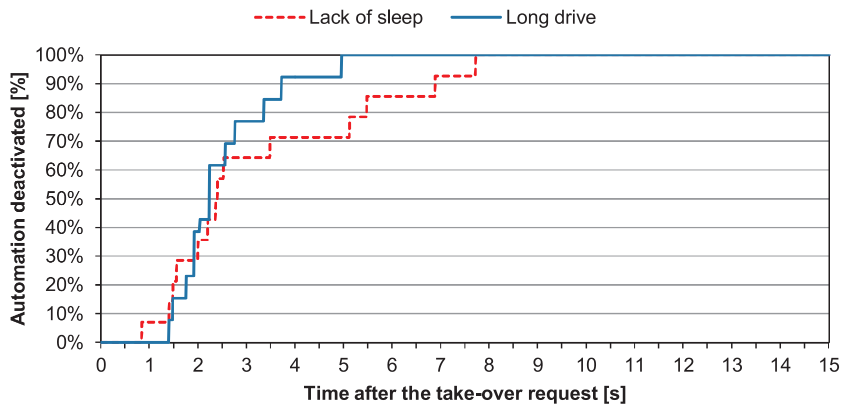

Fig. 14. Cumulative percentages of drivers who had deactivated the automation after the take-over request.

(e.g. Gold et al., 2013; Melcher et al., 2015). Considering that the drivers in this study did not have a non-driving task on a tablet pc which they had to interrupt and put down before deactivating the automation, automation deactivation times for some fatigued drivers could potentially be comparable to those of highly distracted drivers.

We therefore argue that an automated driving system should actively prepare and compensate for delayed reactions from fatigued drivers. The system needs to understand the drivers' state to be able to heuristically judge the drivers' readiness for a take-over and to adapt take-over times, steering support, braking support and other supportive measures accordingly. Such a system may even have to decide that based on the drivers' state it is safer to directly transfer to a safe state instead of trying to hand back control to a fatigued or distracted driver, if it cannot provide a sufficiently long time buffer for a take-over.

4.3. Drivers with automation need additional time to build situation awareness

These arguments apply even more so when we consider additional measures for a successful return to manual driving. Gold et al. (2016) and Vlakveld (2015) argue, that not only the take-over time but also the time to regain situation awareness after a take-over request will influence the quality of a drivers' reactions and his or her ability to detect hazards and threats. Similarly, in a previous study (Vogelpohl et al., accepted) we discuss eye-tracking measures which may be indicative of situation awareness after a take-over request. In our previous study, we found the first glance to the side mirror and the first glance to the speed display to be delayed for up to 5 s for highly distracted drivers with automation compared to manual drivers.

Analogous to the results from the previous study, we found a delay in the reactions of the drivers with automation concerning the first glance to the speed display. The speed display was essential to the understanding of the take-over situation, as a heavy rainfall would motivate most drivers in real world driving to adapt their speed to the road conditions. The delayed reactions for the first glance to the speed display in the drivers with automation could therefore be an indicator, that only after the deactivation of the automation did the drivers start to form an understanding of the surrounding environment and the road and traffic conditions in which they suddenly found themselves after the take-over request.

However, for this measure of situation awareness after a take-over we found no significant differences between the drivers who had become fatigued through a long drive and the drivers who had become fatigue through a previous lack of sleep. It appears therefore, that in general drivers with automation need additional time to regain situation awareness after a take-over. This process can take even longer if the driver was previously in a state which impairs his or her ability to relocate attention, i.e. highly distracted through a non-driving task or fatigued through a lack of sleep or sustained attentional demands.

In contrast to Vogelpohl et al. (submitted) we did not find a delay in the first glance to the side mirror to be indicative of driving with automation. This may be due to the take-over scenario used in this study, which could be resolved by staying in the same lane after the take-over and therefore did not require the drivers to switch lanes. As switching lanes is associated with frequent glances to the side mirror (e.g. Henning et al., 2008; Salvucci and Liu, 2002), the drivers who did not switch lanes simply failed to look at the side mirror during the analyzed time period after the take-over request.

Indirectly, this analysis of mirror viewing behavior also revealed a marked difference in the choice of braking/steering behavior between the drivers with automation and the manual drivers. While manual drivers tended to switch lanes to overtake the lead vehicle which started braking after the take-over request/warning signal, the drivers with automation often chose to stay in the lane behind the braking lead

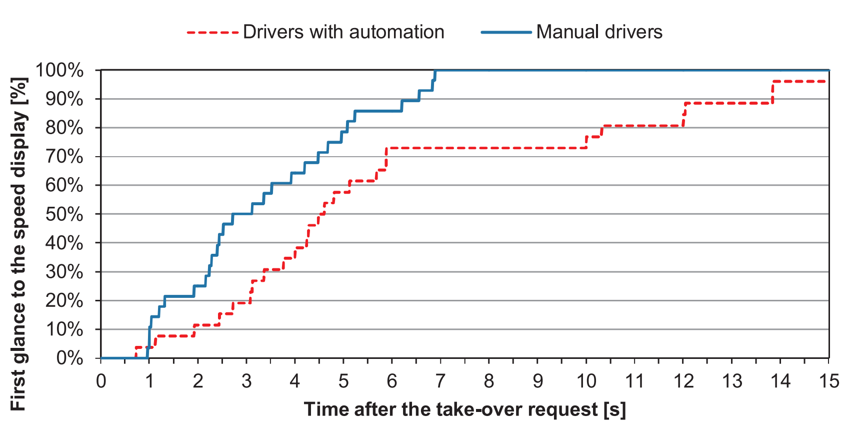

Fig. 15. Cumulative percentage of drivers who had looked at the speed display after the take-over request.

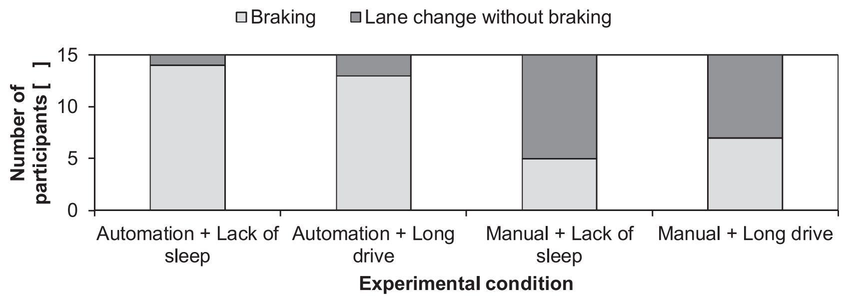

Fig. 16. Categorized braking/steering reactions of the drivers to the braking lead vehicle.

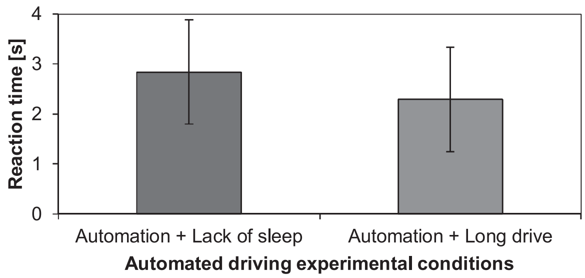

Fig. 17. Mean brake reaction times and standard deviations in the automated driving conditions.

vehicle. This behavior could reflect a need to gain more time after a take-over, which would indicate that the time taken to deactivate the automation was not sufficient to rebuild an awareness of the driving situation which is comparable to that of manual drivers. By reducing the complexity of the situation after the take-over and staying in the lane behind the braking lead vehicle drivers with automation may have tried to reduce the cognitive demand of mentally and physically switching from one task (monitoring the automation; trying to stay alert) to another task (driving; actively perceiving the surrounding traffic). There is therefore a cognitive task switching cost associated with the transition from driving with automation back to manual driving (e.g. Monsell, 2003; Vollrath et al., 2011; Wickens et al., 2013), which can lead to behavior different from manual drivers and which could potentially influence the flow of traffic and the safety of drivers following the vehicle with automation.

Automated driving systems should actively support the driver in the process of rebuilding situation awareness in the time frame until he or she switches off the automation, but also in the time frame after the deactivation of the automation. This will help the driver to gather information about the traffic situation more efficiently and to make better decisions about the point in time where he or she disengages the automation and about the appropriateness of driving maneuvers after the take-over.

4.4. Distraction preferable to fatigue in automated driving?

Given that in our study the drivers with automation…

(1) frequently became fatigued even if they did not previously suffer from a lack of sleep
(2) were sometimes slow to react to take-over requests and
(3) may have deactivated the automation before being sufficiently aware of their surroundings,

the question arises if allowing distraction during automated driving may help to prevent or delay the evolution of fatigue (bullet point 1), and possibly make no difference to the reaction times (bullet point 2) and the reaction quality (bullet point 3), as discussed by Miller et al. (2015).

Building on this assumption it may be preferable to allow drivers to distract themselves during highly automated driving and to make that distraction controllable through the automated driving system. This would allow the system to know if the driver is available through his or her inputs in the non-driving task, and it may also enable the system to safely switch off the task when the attention of the driver is required. Constricting the non-driving task to controllable devices or in-car infotainment systems could also be an opportunity to provide drivers with constant feedback about the driving environment to keep them in the loop and to provide information about the take-over situation ahead if a take-over request is issued.

Future studies should investigate if the effects of fatigue and a lack of sleep during automated driving can be mitigated through non-driving tasks. Such tasks should be easy to interrupt through the automated driving system, as well as easy to interrupt from a user's perspective. In a recent study, Saxby et al. (2017) investigated whether a simulated phone conversation during automated driving could mitigate the effects of fatigue. While a phone conversation would satisfy the criteria discussed above, the authors found no positive effects of this task on the ability of fatigued drivers to take back manual control after automated driving. Possibly, motivating and engaging tasks as proposed for manual driving by Oron-Gilad et al. (2008) may be more effective and better suited to ensure driver availability during higher levels of automated driving.

Other driver states which might have an influence on the take-over time and take-over performance of drivers need to be identified. This will help to design systems which can predict driver behavior and provide appropriate support during transitions to manual driving. Additionally, reliable indicators of situation awareness after a take-over request need to be found, which will provide the systems with information as to whether a driver has fully understood a traffic situation when he or she decides to deactivate the automation.

4.5. Limitations of this study

This study was conducted in a driving simulator setting which may have influenced the development of fatigue in some of the drivers. Crashing or failing to react to sudden hazards would not have directly impacted the health of the drivers, which may have made them more relaxed than in an actual car. Additionally, some studies suggest that motivation can influence the ability for sustained attention over time (e.g. Nachreiner, 1977). However, the drivers knew they were taking part in an experiment which could involve take-over requests and critical driving situations. While the participants did not know the frequency of these situations, there might have been some effect of expectancy, which could have kept them at a higher level of alertness than in real world driving.

In addition to asking the participants in the *Lack of* sleep condition to sleep for a maximum of 5 h, we invited them into the driving simulator at nighttime. In contrast, the participants in the *Long drive* condition were invited into the simulator during daytime and did not suffer from a lack of sleep. Thereby, hours of sleep in our study are confounded with the time of day, as well as with the hours of wakefulness. We chose this approach to research the development and effects of generalized driver fatigue (as defined in May and Baldwin, 2009) in two specific use cases of automated driving: Using the system to drive home at night after work and poor sleep quantity and using the system fully awake, but for a prolonged duration. Future studies should aim to clearly identify the sources of fatigue during automated driving and to differentiate how different types of driver fatigue during automated driving can influence take-over performance.

For driving without automation, some studies have already suggested that specific effects on driving performance may to be related to specific sources of fatigue (e.g. sleep deprivation vs. time-on-task). In a driving simulator study on the effects of partial sleep deprivation and long driving time by Otmani et al. (2005) the authors found that driving performance as measured by standard deviation of lateral position and the frequency of steering wheel movements was not affected by partial sleep deprivation but was strongly influenced by time on task. However, right edge-line crossings were mainly influenced by partial sleep deprivation. These results are similar to Fairclough and Graham (1999), who also found driving performance to be mostly uninfluenced by partial sleep deprivation, except for the number of near-lane crossings. Therefore, in our study effects on driving performance may have been more strongly influenced by the time on task of each individual driver than by the lack of sleep in the respective experimental condition. Differences similar to those observed by Otmani et al. (2005) and Fairclough and Graham (1999) could influence the severity and effects of driver fatigue from different sources during driving with automation and should therefore be considered for the design of assistance systems and investigated in greater detail in future studies.

We used trained raters to score fatigue over the progression of the drive. Wierwille and Ellsworth (1994) discuss that using trained raters to score drowsiness on a single item scale may not give a "true drowsiness level "(p. 579), due to the differences in the definitions of drowsiness between the raters. However, correlations of the ratings with other eye-based measures such as PERCLOS were high, and correlations with other physiological measures at least moderate, indicating the validity of the measures of trained raters. In our study, the trained raters were not asked to provide an immediate estimate of the drivers fatigue level, but recorded objective facial and behavioral indicators of fatigue (such as long blinks and mannerisms), which were later combined to form the exact fatigue level. Thereby, we hope to have reduced the influence of the raters on the fatigue ratings, but could not completely avoid it.

Drivers in the study were not aware that they were being observed regarding their fatigue levels. However, the trained raters knew the purpose of the study and were informed about the fatigue group to which the participants they were rating belonged (i.e. *Lack of sleep* or *Long drive*). This prior knowledge about the sleep durations of the participants might have influenced the judgment of the raters. However, the raters were trained to only count behavioral indicators of fatigue and perform the actual fatigue level ratings based on these objective indicators only after the end of the experiment. The validity of this measure of fatigue is additionally supported by a high correlation between the subjective fatigue ratings given by the drivers and the ratings from the trained raters.

The raters scored the progression of fatigue for intervals of 60 s every 5 min. The sampling duration of 60 s was chosen based on the recommendations in Wiegand et al. (2009), who discuss durations of a minimum of 30 s of video material to enable rater scoring of fatigue. The sampling rate of 5 min was chosen as a compromise between the workload for the trained raters and the risk of missing indicators of fatigue during the non-rating periods. Rating the fatigue level required high levels of concentration from the trained raters, as it was performed "live". Therefore, continuous ratings for the duration of 55 min or a higher sampling rate would likely have reduced the quality of the ratings. However, the choice of the intervals may have had an influence on the fatigue ratings and the raters may have missed indicators of fatigue during the non-rating intervals.

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