MASTER

Failing gracefully
effect of HMI augmentation on recovered situation awareness after transfer of driving control

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Failing gracefully:

Effect of HMI augmentation on recovered situation awareness after transfer of driving control

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Abstract

Currently driving automation systems become available that automate the primary driving task but may transfer control back to the driver at certain system limitations. Automation is known to affect the awareness a person has in fulfilling a task, called situation awareness. It is known that, when a driver receives manual control from automated driving, driving performance is affected and safety hazards may occur. The current study, in addressing this safety issue, investigates the effect of a display that supports recovery of situation awareness during a transfer of control using a driving simulator. Half of the participants did not receive display support. Situation awareness was measured for two types: display information and other driving information. An interaction effect was found between subject condition and situation awareness information type. The results partially support the hypothesis and suggest a potential of such a display to support situation awareness. Further implications are discussed.

Contents

List of abbreviations

ACC adaptive cruise control

ADAS advanced driver assistance system

BASt Germany Federal Highway Research Institute

DENM decentralized environmental notification message

HAD highly automated driving

HF human factors

HMI human-machine interface

ITS intelligent transport system

LKA lane keep assist

NHTSA National Highway Traffic Safety Administration

SA situation awareness

SAE Society of Automotive Engineers

SAGAT Situation Awareness Global Assessment Technique

SART Situation Awareness Rating Technique

TOR take-over request

Chapter 1

Introduction

1.1 Background

The current thesis reports on a literature review and experimental study relating to drivers' situation awareness when they are required to switch from fully automated to fully manual modes of vehicle control. The study has been commissioned and facilitated by Altran Netherlands B.V.. Altran is a technical consultancy, active in a variety of high-tech domains such as energy, telecommunications, aerospace and mobility. A current joint activity is an implementation of a decentralized environmental notification message (DENM) service, which is an intelligent transport system (ITS) vehicular communication standard (ETSI, 2010).

The point of departure for the current study was to investigate the human factors (HF) implications of recent ITS developments, such as DENM, for car drivers, with an emphasis on safety implications. Several explorative interviews with related experts have been conducted to further focus of the research topic. Specifically, these experts include the following Altran-employed consultants and their respective ITS-related client:

- mr. Joost van Doorn (NXP Semiconductor, a semiconductor manufacturer)
- ir. Jeroen van der Werf (Rijkswaterstaat, a Dutch infrastructure agency)

The following external experts have been interviewed:

- ir. Roland van Venrooij (TomTom, a navigation and mapping product manufacturer)
- ir. Frank Benders (TNO, a non-profit research institute in applied sciences)
- dr. Willem Vlakveld (SWOV, a non-profit traffic safety research institute)
- prof.dr. Dick de Waard (RUG, University of Groningen, Faculty of Behavioural and Social Sciences)

While this list of interviewees should not be considered an exhaustive orientation on HF in ITS, the interviews have yielded a view on ITS developments in the Netherlands from multiple angles, including industry stakeholders (TomTom, NXP), government (Rijkswaterstaat) and research institutes (SWOV, TNO, RUG).

A common notion among the experts is the difficulty of ITS application development because of the interdependency with infrastructure and other facilitating services. For example, car manufacturers are hesitant to develop ITS features while it is still unknown how the communication standards with infrastructure and between cars will develop and vice versa. Also, all experts agree that, in the light of upcoming ITS developments such as automated driving and advanced information systems, the role and the responsibilities of a car driver is expected to change and such implications must be investigated. An ITS development that is mentioned frequently is automated driving: several current developments seem fostered by the bigger goal of eventually enabling autonomous driving. Examples are the long-term vision of Rijkswaterstaat, truck platooning research at TNO, ITS demo cases by NXP and HF research in automated driving at SWOV.

Differences amongst the experts seem to mainly revolve around the circumstances of how ITS will develop in the near future and the roles of the involved parties, e.g. some consider ITS developments in a rather isolated, incremental process while others expect future ITS to disrupt virtually all aspects of mobility.

The exploration has brought several insights into current developments in ITS and has provided suggestions to focus our HF study. Especially the HF implications of automated driving appear to be a relevant and contemporary subject that still demands further research, especially in terms of safety. Based on the exploration the research subject was therefore further focused on the HF in automated driving, in particular the safety implications.

1.2 Human factors in automated driving

The experience of driving a car has changed drastically in the last half century. It has evolved from dealing with simple and primitive planning and operation to complex and sophisticated system management, such as cruise control and navigation systems (Akamatsu, Green & Bengler, 2013). Some of these new systems aim at performance (Alkim, Bootsma & Hoogendoorn, 2007) and traffic safety (Kuehn, Hummel & Bende, 2009), while others offer comfort facilities for the driver (Brookhuis, De Waard & Janssen, 2001). Clearly, these innovations caused a change in the environment of the driver and its role as a car operator and road member. Automotive HF research investigates the implications of these developments for the driver (Akamatsu et al., 2013).

The majority of current driving accidents are caused by driver error (Singh, 2015). To address such human errors by taking over a part of the driving task, new advanced driver assistance system (ADAS) are developed (Kuehn et al., 2009). This type of automation of drivings tasks, however, faces us for a number of new HF challenges that are yet to be overcome (Norman, 2015). These challenges are critical in that they typically concern how a driver deals with unexpected system behaviour. Without sufficient HF consideration such ADASs may not achieve the goal of making driving more safe (Creaser & Fitch, 2015).

The current study focusses on the highly automated driving (HAD) scenario where control unexpectedly is transferred back the driver due to some HAD system limitation, which is a likely scenario for HAD in the near future (NHTSA, 2013). Challenges with such control transfers have already been investigated thoroughly (De Winter, Happee, Martens & Stanton, 2014; Z. Lu, Happee, Cabrall, Kyriakidis & de Winter, 2016; Vlakveld, 2016). One important challenge caused by HAD is the deterioration of the awareness of the driving conditions, called situation awareness (SA). The affected SA results in a performance drop with drivers, which increases the probability of an accident (De Winter et al., 2014).

This study investigates a possible solution to affected SA caused by HAD. This was done with a driving simulator lab experiment by exposing participants to an experimental information display, which augments information about driving conditions during the control transfer. In chapter 2 the rationale behind the research question is discussed using a literature review. Chapter 3 presents the method of the driving simulator experiment. In chapter 4 the results of the experiment are presented and in chapter 5 the implications, limitations and further recommendations based on the current study are discussed.

Chapter 2

Literature review

2.1 The task of driving

Driving a vehicle on the road involves the risk of getting into an accident. The National Highway Traffic Safety Administration (NHTSA) estimated 94% of crashes in the US within years 2005 till 2007 to have been caused mainly by the driver, which represents 2,046,000 crashes (Singh, 2015). Within those driver-caused crashes 41% (or 845,000 crashes) has "recognition error" as the critical reason, which they described as "drivers inattention, internal and external distractions, and inadequate surveillance" (Singh, 2015, p. 2). Driving mostly demands visual attention, compared to other modalities such as auditory or haptic (Gugerty, 2011). At the same time non-driving distractions, such as using a smartphone or a radio system, also require visual attention. These distractions can affect the driving safety by, for instance, causing increased hazard response time (Horrey, Wickens & Consalus, 2006). Visual attention is therefore considered an important aspect for safe driving, and distractions from the driving task are likely to be the cause of a considerable amount of traffic accidents.

The goal of driving a vehicle has generally been differentiated into three types, being strategic, tactical and operational (Michon, 1985). The strategic driving goal concerns navigational tasks, such as route planning and route decision making, and typically are rather static, not time-critical tasks. Strategic goals require knowledge of the road network and translate into general plans concerning the journey that is to be made. The tactical driving goals concern manoeuvring the vehicle on the road and deals with more timely matters, such as obstacle avoidance and overtaking. Tactical goals require knowledge of the current traffic- and road situation and a prediction of their immediate future state, such as lane position, presence and movement of other vehicles in the area and current and desired driving speed. Operational driving goals concern the translation of decisions made on the tactical level into the actual control of the vehicle. To execute these controls information about the vehicle system and vehicle state are involved, such as the steering wheel sensitivity and position. Where strategic and tactical goals mostly involve conscious processes, operational goals are generally well-learned, unconscious routine actions. There is a clear interaction between types of driving goals. For instance, the decision to exit a highway (tactical goal) depends on the destinations this exit can take you (strategic). The driving goal differentiation gives more insights into the information that is required for each set of subgoals. Moreover, it becomes clear that immediate driving safety issues mainly emerge from tactical and operational driving goals.

Performing a task, such as driving a vehicle, requires a mental representation of the situation with regard to that task. Such a mental representation is known as situation awareness (SA) and is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1988a, p. 97). The term was introduced in the aircraft pilot domain but has since proven an important concept in HF research across many domains, including automotive, and despite debates about its viability it is increasingly used and broadly accepted (Wickens, 2008). As the original definition implies, SA can be differentiated into three hierarchical phases, known as SA levels: perception of the elements in the environment (1), comprehension of the current situation (2) and projection of future status (3). To compose a clear and specific understanding of the SA in a given environment and a given set of tasks one can use the SA levels to map elements (i.e. things, their meaning and their future state) that are needed to fulfil the task and subtasks at hand (Endsley, 1995). An example of the elements of SA at different levels for a specific driving task is safely dealing with a fellow road user. Level 1 SA would represent the perception of the road user, such as "there is a car breaking in front of me in my lane". Level 2 SA would entail the current safety situation with regard to the fellow road user, such as "I have a safe headway from the breaking car in front of me". Level 3 SA would include a prediction of the future meaning regarding the fellow road user, such as "the car in front of me is breaking and I might therefore arrive at an unsafe distance to the car". It should become clear that the complexity of a driving task will cause the SA of a driver at any given point to entail a variety of elements that apply to the current driving situation. At the same time the contents of the SA may vary during a drive depending on the current subtask at hand.

To be able to study SA for driving a vehicle, Matthews, Bryant, Webb and Harbluk (2001) have introduced a model that maps the three SA levels onto the generally accepted subgoals of driving, being strategic, tactical and operational (Michon, 1985) (see figure 2.1). The model assigns the degree of involvement of SA levels on the respective characteristics of the driving goals. A strategic driving goal mainly consists of level 3 SA elements that concern planning operations but also deals with moving the vehicle in the planned route and operating the vehicle accordingly. Tactical goals mainly deal with the immediate meaning of the surrounding to traverse through traffic in a safe and orderly fashion. Operational goals, because of their unconscious nature, entail little SA. The limited SA that is needed is used for perceiving and understanding the controls that apply to the task. Note that all driving goals require some degree of perception (SA level 1) and understanding (SA level 2). Because of the focus of the current study on driving safety the main concern is the driving subtask of accident avoidance, which is considered a tactical task (Matthews et al., 2001; van den Beukel & van der Voort, 2013). Based on the model of Matthews et al. (2001) we therefore claim that accident avoidance as a driving subtask mainly requires SA elements at the perception- (1) and comprehension level (2).

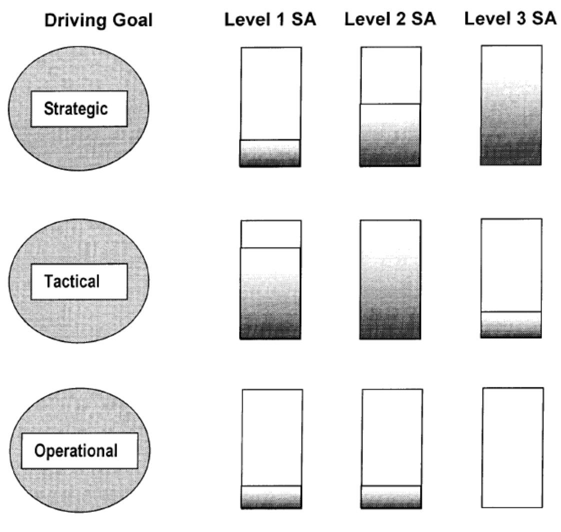


Figure 2.1: Sub goals of driving mapped onto levels of SA (Matthews et al., 2001, p. 28)

In conclusion, the task of driving a vehicle is considered a complex and dynamic task that demands a great deal of attention. If not sufficiently attended it is known to cause a high number of accidents. Operational and tactical driving subgoals are closely related to accident avoiding activities. The SA that is required for such activities will mostly be of level 1 and level 2.

2.2 Driving automation and information systems

A new automotive development is an advanced driver assistance system (ADAS), which supports the driver in driving the car. ADAS may refer to several different types of functionalities, such as cruise control, precrash systems, lane departure systems, parking assistance systems, etc. (Shaout, Colella & Awad, 2011). When adopted, such ADASs are expected to reduce the number of traffic accidents, improve the comfort of driving a car and increase its performance (Beiker, 2012). Accident reduction is achieved by supporting the human driver in some critical driving task, such as an anti-lock braking system. Increasing comfort is done by taking over some driving task and therefore reducing workload, such as cruise control. Performance increase can also be done by supporting or replacing a certain task, such as an automatic engine start-stop system. Therefore, ADAS commonly share the property that they support or replace some aspect of the driving task by an automated system that was formerly executed by the driver.

Currently ADAS systems enter the automotive market that feature automation of the primary driving tasks of lateral (i.e. steering) and longitudinal vehicle control (i.e. accelerating and decelerating). Automated longitudinal vehicle control is commonly known as adaptive cruise control (ACC). An ACC control system functions similarly as a normal cruise control system in that a setpoint speed is maintained. An ACC will, however, adjust the driving speed when a vehicle in front of the vehicle with ACC comes too close. ACC will return to setpoint speed once the headway is clear again. Automated longitudinal vehicle control is achieved by an ADAS system called lane keep assist (LKA). When activated LKA controls the heading of the car based on the relative lateral position between lane markings (M. Lu, Wevers & Van Der Heijden, 2005; Shaout et al., 2011). A combination of a lateral (LKA) and longitudinal (ACC) control system is commonly known as highly automated driving (HAD). These HAD enabling ADAS systems may only function properly within certain circumstances, such as weather conditions and road conditions, due to physical limitations of sensors, processing capacity or actuation limitations (Shaout et al., 2011). Limits to the functioning circumstances of such systems are called system boundaries. When such an ADAS reaches such a system boundary it will typically disable itself and return control to manual, in other words, to the driver. This is one of multiple possible control transitions that can occur in the situation of HAD. Such transitions can be classified by identifying the control initiator (i.e. driver vs. automation), the resulting controller (i.e. driver in control vs. automation in control) and underlying reason of why the control transfer occurs (i.e mandatory vs. optional) (Z. Lu et al., 2016)). According to this classification, a control transfer where an ADAS reaches a system boundary after a period of engaged HAD is considered a mandatory transfer, resulting in driver control, initiated by automation.

To investigate the implications for a driver, multiple approaches exist that characterise automation with regard to task execution (Flemisch, Schieben, Kelsch & Lper, 2008). Parasuraman, Sheridan and Wickens (2000) introduced a widely used model. Their model differentiates the level to which automation takes place across four stages of human information processing, being information acquisition, information analysis, decision selection and action implementation. Each of the processing stages can be automated to a different degree, depending on the characteristics of the automated system (see figure 2.2). A higher degree of automation can be achieved by both automating later stages of processing and by a higher automation level within stages. The model allows for a specification of the role of the operator and the automation respectively in some automated system. For instance, an ACC as automation functions on a high automation level across the first three stages of information acquisition (i.e.: automated speed measurement and headway measurement), information analysis (i.e.: processing the sensory measurement through an algorithm relative to the speed setpoint and headway setpoint), decision selection (i.e.: output acceleration or deceleration based on processing). The fourth stage, action implementation, allows for operator involvement by intervening and cancelling any automated speed adjustment, and is therefore of a lower degree of automation. In this sense the operator has an intervening role in the action implementation of an ACC automation system.

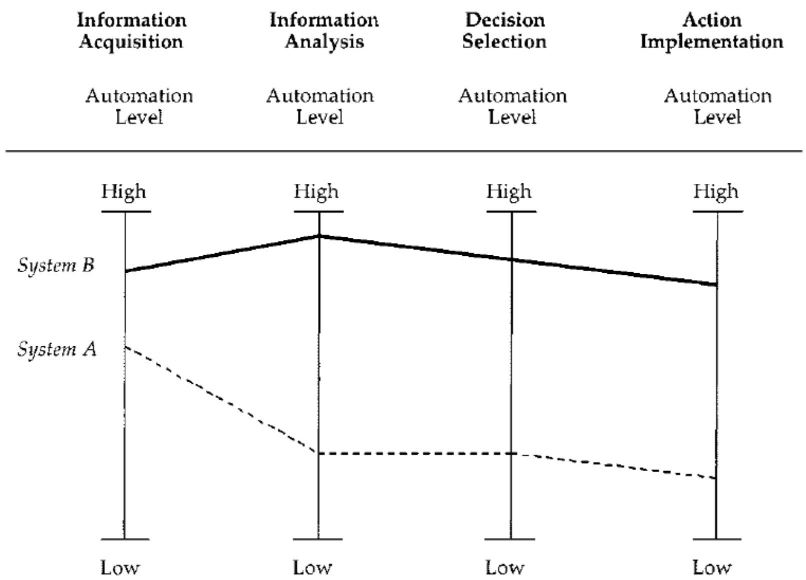


Figure 2.2: Automation model by Parasuraman et al. (2000) demonstrating two different levels of automation

Next to developments in ADAS, a different kind of automotive development currently takes place, called intelligent transport system (ITS). Developments in ITS make information available concerning traffic conditions (e.g. road/traffic-, road works- and alternative route information) and driving safety (e.g. obstacle-, congestion-, road weather- and emergency vehicle warnings) (Wei, 2011). Most applications that enable such 'awareness' for a vehicle rely on a principle called cooperative systems, which are a type of communication between vehicles (car-to-car communication) and of vehicles with the road (car-to-infrastructure communication) (ETSI, 2010). Developments of such ITS technologies take place in the United States, Europe and Asia (Grumert, 2011; Santa, Pereguez, Moragn & Skarmeta, 2014). Advanced sensors and communication across an entire fleet of vehicles and information systems are expected to offer valuable data for future vehicles, by providing relevant and valid information to both the driver and automated driving systems (ADAS).

Based on such automation models and given the different developments in automotive driving systems, several road authorities have developed vehicle automation models that aim to integrate these developments into general vehicle automation levels. The Society of Automotive Engineers (SAE), the Germany Federal Highway Research Institute (BASt) and the NHTSA have developed such models. The models have many commonalities in their definitions of automation levels (Smith, 2013). NHTSA's five level (level 0 - level 4) vehicle automation model describes a controlling role for the driver for all but the highest automation level (NHTSA, 2013). In that sense, level 4 vehicle automation fits the highest level of automation across all information processing phases with regard to Parasuraman et al. (2000). HAD meets both NHTSA's level 2 and 3 vehicle automation descriptions. The general difference between these levels is the monitoring role within driving automation. At level 2: "The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely." (NHTSA, 2013, p. 5). At level 3 the HAD system is able to take full control, while: "The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The vehicle is designed to ensure safe operation during the automated driving mode." (NHTSA, 2013, p. 5).

From these driving automation models and their underlying automation systems it becomes clear that the driving experience changes drastically when HAD is implemented. The driver will share the autonomy of lateral and longitudinal vehicle control with some automated system. The implications these changes in driving tasks may have for the driver will be discussed in the upcoming sections.

2.3 Human performance and automation

Applying automation to a formally manual task is widely known to, aside from the intended positive effects, potentially cause negative effects to task performance (Onnasch, Wickens, Li & Manzey, 2013). The general notion about these negative effects is that the change of the human role from manually performing the task to becoming monitor of an automated system is not beneficial for the human performance. Two major factors are identified to underlie this decreased performance: loss of skills related to the task at hand and loss of SA (Endsley & Kiris, 1995). Skill loss can occur when an operator has less opportunity to train the ability of manually performing the task at hand. Given the predefined system boundaries of the NHTSA driving automation at levels 2 and 3, a driver is expected to frequently turn to manual control and therefore will still be able to train the ability of driving the vehicle, at least for automated systems that become available for the upcoming years (2017-2025) (Trimble, Bishop, Morgan & Blanco, 2014). Skill loss will therefore not be treated further in this study.

Automation is identified to directly affect SA through three mechanisms: change in vigilance and complacency in monitoring, a passive instead of active role in the control of the system at hand, change in feedback by the system to the operator (Endsley, 1996). The human operator tends to place too much trust in the functioning of an automated system. This over-reliance, also called complacency, could cause operators to not monitor the automation to the extend needed. The lack of perception, comprehension and projection of the automated system will, by its definition, negatively affect the level of SA. Where an active role in the control of a system requires processing of information relevant to the task, a passive role will only require this information to be observed. Detecting the need for manual intervention and the reorientation after control has transferred to manual will therefore become affected when having a passive role in an automated system. Lastly, by its design, automated systems may lack in providing feedback to the human operator about its functioning and status. Compared to manual operation, an automated system could provide information that is less salient (e.g. an alarm instead of a shaking car when accidentally entering the roadside), is in a form that is harder to process (e.g. a numeric speed indicator instead of analogue) or even an entire lack of feedback due to poor user interface design. Contrary to intended workload reduction, ADAS may increase workload in some circumstances where an operator takes effort in perceiving and interpreting the automated system (Matthews et al., 2001).

The effects of automation on task performance have been investigated for HAD. Several literature reviews exist that provide overviews of such studies (De Winter et al., 2014; Vlakveld, 2016; Z. Lu et al., 2016; Merat & de Waard, 2014). Although alternative approaches exist for evaluating automated driving scenarios, the human factors (HF) paradigm with SA and workload as central concepts, is dominant in this field (Vlakveld, 2016). A common scenario in these studies is the transition of task execution from automated to manual, in which a driver first experiences an automated driving situation and at some point receives back control by disabling the automation. Such a scenario is expected to take place at system boundaries of the involved ADAS. This event is also called a take-over request (TOR). Overall, the results from those reviewed empirical studies is in line with the theoretical effects of task automation. That is, a higher level of automation negatively affects driving performance after control is transferred back to the driver (TOR), compared to when no automation introduced. Lowered driving performance has been expressed in several parameters, such as longer reaction times to hazards (Dambock, Weigerber, Kienle & Bengler, 2013), eye fixation on the road (Merat, Jamson, Lai, Daly & Carsten, 2014), steering wheel- and lane position (Mok et al., 2015) and use of braking (Gold, Dambck, Lorenz & Bengler, 2013). These effects on performance have been discussed to be directly caused by lowered SA, specifically through automation complacency and a passive operator role (De Winter et al., 2014; Z. Lu et al., 2016).

Aside from measuring task performance, the effect of driving automation can also be determined more directly through SA measurement. There are different ways in which SA can be measured in a driving situation. One distinction is online vs. offline measurement methods. Online methods measure SA indirectly through tracking driving behavior, e.g. eye tracking, driving performance or event detection, while the driving task is not interrupted. Offline methods interrupt the driving task and directly measure SA by asking the participant a series of questions concerning the critical elements of the driving situation, e.g. whether a driver has noticed an incoming obstacle or is aware of other vehicles in the area (Gugerty, 2011). For a comprehensive overview and comparison of SA measurement methods, see Salmon, Stanton, Walker and Green (2006).

The effects we know that HAD can have on driving performance demand further investigation into how its potential problems can be prevented. Specifically, further research is needed into how SA can be at appropriate levels after a TOR to safely take back manual driving control. This is an argument that has been made before by others, while suggesting that without further investigation driving safety may even be worse off (Creaser & Fitch, 2015; Miller, Sun & Ju, 2014; Onnasch et al., 2013; Walker, Stanton & Young, 2008).

2.4 Supporting situation awareness recovery

To address SA in an automated driving scenario the general notion is to design the automated system in such a way that a driver remains informed about the driving situation and the automated system status (Creaser & Fitch, 2015; Merat et al., 2014; Seppelt & Victor, 2016; Trimble et al., 2014). This information exchange largely relies on the vehicles human-machine interface (HMI). Introducing such an HMI to support SA recovery may have negative side-effects, however. The driving information density, style and content type that is conveyed by means of a display may cause an increase in the drivers workload and demand attention to an extent that could defeat the purpose of enhancing the drivers SA using ICT (Lee, Gore & Campbell, 1999; Tufano, 1997). Display design guidelines with automated systems exist that are aimed to enhance SA (Endsley, 1988a; Matthews et al., 2001). Some related work has been done in this field, which is discussed next.

Using an interactive driving simulator setup, Lee et al. (1999) have investigated the effects of a variety of driving warning message display types on compliance behavior and driving performance in terms of safety. Messages varied (within-subject) in message style (command vs. notification, e.g.: reduce speed vs. icy roadway), message modality (visual text vs. auditory) and information availability (display and roadway vs. display only vs. roadway only vs. neither). Between subjects the message display location differed (i.e. centralized display and both speakers, vs distributed, different messages across different displays and speaker locations), effect of gender assessed and two age groups were differentiated. All participants (N = 32) experienced four out of six possible driving scenarios during the experimental procedure. Aside from message compliance and driving safety, SA was directly measured through the Situation Awareness Global Assessment Technique (SAGAT), originally introduced by Endsley (1988a). SAGAT is an offline SA measurement method that uses a 'freeze probe': the simulation is suspended and the participant is asked specific questions about elements that could have been noticed during the simulation and are considered important elements in the SA of someone performing a certain task. The number of correct questions determines an 'SA-score' and determines the current SA of the participant. Most interesting results from this study were that warning compliance increased by the presence of warning messages, especially by the commanding type of message, and no effect found for other types of variations. At the same time the commanding message type decreased the driving safety expressed by the participants. The availability of warning message information affected SA in that information had to be redundant (both display and roadway information available) for SA to be of a sufficient level, which in line with the driving safety). The authors discussed that the limited availability of the warning messages in some conditions led to an inappropriate distribution of attention and, in turn, caused a limited development of SA. The limited evidence for better response for visual types of messages argues for visual instead of auditory warning messages. The authors emphasize the potential negative effects a safety information system may have on the actual driving safety as their study suggests.

Lorenz, Kerschbaum and Schumann (2014), in a driving simulator, performed an experiment using an automated vehicle transfer of control scenario and compared how two versions of an augmented reality display design could improve the quality of the driving behavior. Forty-six participants were assigned to one of the display conditions (between-subject) and a baseline condition with no display. During the automation phase participants were distracted from the driving situation to represent a period of inattention, which is a predicted scenario for driving an automated vehicle. The two display designs both projected a graphical area on the simulated roadway that indicated a manoeuvre instruction to avoid an obstacle ahead. The 'red' condition emphasized a 'barrier' that made the obstacle more salient and the 'green' condition projected a safe trajectory to emphasize a pathway away from the obstacle. Driving performance measured with several timing variables and with simulator control inputs to derive the possible improvements that the display designs caused to the participants' awareness of the obstacle and their ability to handle the vehicle correctly. SA was not measured directly. Results showed no clear improvements on how quickly participants were able to respond to the approaching obstacle. Participants in the display conditions gazed to the side mirrors later than in the no-display condition, which the authors explain could be caused by additional attention needed to interpret the display message before a lane change initiated. A difference was found between display designs in how participants reacted to the obstacle: the red group had a stronger reaction in terms of braking compared to the green group, which the authors explained could be because the red message style conveys a stronger warning and urgency compared to the green message.

Van den Beukel and van de Voort (2013) used a driving simulator experiment to test the validity of two SA measurement methods: the earlier mentioned SAGAT method and the Situation Awareness Rating Technique (SART). SART is an offline, self-rating technique that assesses the SA of a participant concerning a very recent task. Both SART and SAGAT are popular SA measurement methods. SART has proven to be useful, although its validity has been questioned because of its high correlation with workload measurements (Charlton, 2002). In this experiment both measurement methods have been tested to investigate the effect of the time between transfers of control from automated to manual driving mode and a critical road condition on SA. Participants (N = 43) completed 16 different trials during which control transfers occurred. The expectation of the authors was that when more time was available for a participant to act upon the road condition, SA would be better able to develop and therefore SA measurements would yield higher scores for higher time conditions. Results show that in general fewer accidents occurred during the trials with less time-critical conditions. Considering the SA measurements, however, no significant correlations have been found between SA scores and time criticality for neither SA measurement methods. The authors explained the poor SAGAT measurement method from a lack of specificity of individual SAGAT probing questions. They recommended to tailor the SAGAT questionnaire to the specific driving situations that occur in the trials of the simulations to reach a better SA measurement.

Although research is done in supporting SA in recovery after a TOR, there is still work to be done in exploring the means by which the HMI of an automated vehicle can contribute to a safe HAD scenario. While previous studies have yielded some suggestions for HMI message type and display style, their findings are still inconclusive and the potential of HMI to support SA recovery argues for more investigation (Creaser & Fitch, 2015). From these previous studies and from what is suggested of HMI implications in this context (Matthews et al., 2001), of specific interest is the relative costs an HMI has for recovering SA versus its benefits.

2.5 Current study

Based on our literature review, we have found that introducing HAD to a driving task causes SA to be severely affected. Specifically, a TOR after a period of HAD is known to cause a lowered SA. Introducing an HMI that supports SA recovery, by augmenting driving condition- and road condition information during a TOR, has the potential to address this safety problem. However, little empirical evidence is available yet that supports this suggestion.

In this study we therefore investigate the effects such an HMI has on the SA of a driver in the event of a TOR from automated driving to manual driving. Our research question is: To what extent does an HMI support the recovery of drivers' SA during a TOR from automated to manual driving mode?

We specifically investigate how the HMI affects the drivers' SA with the augmented information compared to other driving information elements that are not augmented but nevertheless are considered crucial elements in a driver's mental model for safely performing the driving task. Within the described context and based on previous sections, we hypothesize:

- A driver to be more aware of SA elements that are augmented with the HMI
- A driver to be less aware of SA elements to are not augmented with the HMI

Chapter 3

Method

3.1 Design

Using a passive driving simulation, an experiment was performed investigating the effects of human-machine interface (HMI) augmented warnings on drivers' situation awareness (SA) during a take-over request (TOR) after highly automated driving (HAD), i.e. from autonomous driving to user control. We compared participants' performance across two between-subjects conditions (with and without HMI activated), and across 6 different driving situations. Driving scenes were sorted into 6 different sequences using a Latin square pseudo-counterbalanced sequence transformation to control for order effects. Participants were randomly assigned to an experimental condition and order sequence. During HAD participants attended a secondary task that induced distraction from the driving task. See figure 3.1 for an general overview of the experiment.

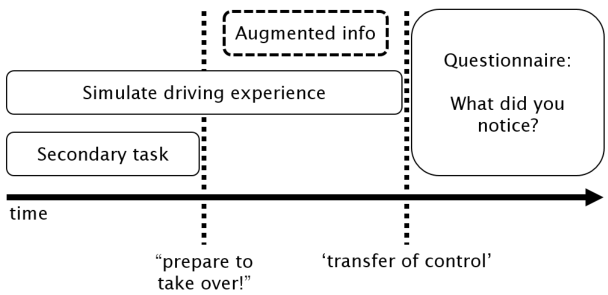


Figure 3.1: Experimental trial overview

After a five-second period of TOR two sets of questionnaires were administered. The first questionnaire measured the SA regarding the driving task. The second questionnaire measured secondary task performance. The same questionnaires were used for both subject groups (i.e. control group and experimental group). An eye tracking sensor measured participants' attention distribution.

The experiment therefore has a two-level between-subject design, where 'experimental condition' is the between-subject factor. The dependent variable is SA, represented by the score of correctly answered questions of the SA questionnaire.

3.2 Participants

A power analysis was performed based on a similar study (McDonald, 2016), which reported an F-test ($F(1,32) = 7.57$, $p = .01$) corresponding with a Cohen's f effect size of .5. With a desired power of .9 the desired sample size resulted in 25 participants for each experimental group.

Two different strategies for participant recruitment were used. Because of high availability, students were directly recruited for participants of age between 18 and 25. Participants with higher age were recruited through an experiment participation registration system, managed by the Human-Technology Interaction research group of Eindhoven University of Technology (the Netherlands). A driving licence was required to participate.

The resulting sample consisted of 27 male and 23 female participants with age between 20 and 76 years (M = 34.2 years, SD = 18.6 years) and driving experience between 0.5 and 45 years (M = 14.4 years, SD = 17.6 years). Note that participant age and driving experience are approximate values, derived from multiple choice answer range options. Random allocation of participants to the subject conditions resulted in similar age distributions for the control group (M = 34.1 years, SD = 17.6 years) and the experimental group (M = 34.3 years, SD = 19.9 years).

3.3 Setting and setup

The experiment took place in a laboratory environment of the Human-Technology Interaction research group of Eindhoven University of Technology (the Nederlands). The experiment setup consisted of a 46-inch computer screen, computer speakers and a computer mouse. The mouse was used to navigate through the experiment instructions and to input questionnaire answers. See figure 3.2 for an impression of the setup. The driving simulation was passive in the sense that participants were not able to interact with the simulated driving. Simulation of a driving experience was to the extend that participants were exposed to driving scenes by means of the computer screen and computer speakers.

Figure 3.2: Setup of the passive driving simulator experiment

A stationary eye tracking system, located in front of the bottom of the screen, was used to track the positions on the computer screen that participants would gaze at. This gazing data was used to provide more insights into the attention strategies that participants exhibited during the driving scenes.

The participant's distance to the screen, the eye tracking system maximum gaze angle and the eye tracking system position were taken into account, resulting in a viewing distance between participant and screen of 100 cm. The seat was adjustable in height in order to position participant's eyes to the height of the middle of the screen, which corresponds to the virtual horizon of the driving scenes. Participants were not able to move the seat around to make sure that they stayed within eye tracking range and at the center of the screen.

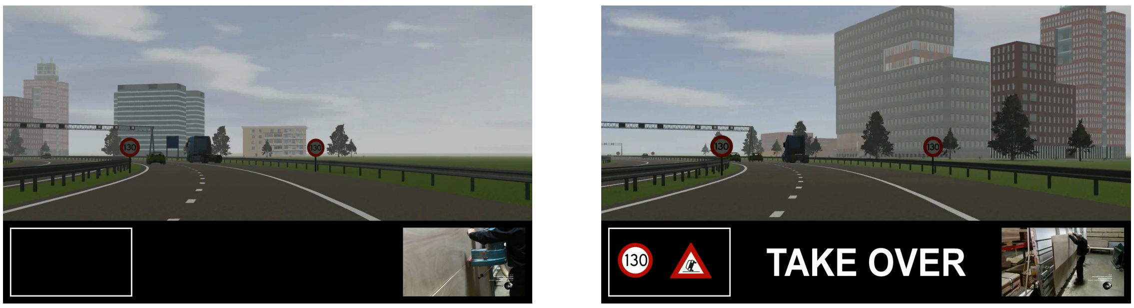
3.4 Materials and apparatus

3.4.1 Driving scenes

Six different virtual driving scenario's (hereafter called 'scenes') were designed using the PreScan simulation tool (TASS International, 2012). Between scenes the situation varied in terms of weather condition, daylight, number of road users, type of surrounding scenery, speed limit and others. Participants were exposed to scenes in which driving situations develop into eventful incidents. Similar to the scenario of Gold, Dambck, Lorenz and Bengler (2013), these scenarios were designed with the aim of simulating the advanced driver assistance system (ADAS) reaching some system boundary and therefore transferring control back to the driver. Every scene contained a unique incident to prevent scenes from becoming predictable. The time length prior to the TOR varied between 13 and 124 seconds (M = 57.8s, SD = 39.3s). See appendix A for specific descriptions of each scene.

The scenes were visible with a rich virtual world with many objects, especially during the TOR, which should challenge participants in focusing on relevant information for gaining SA. Scene scenarios took place on highways since these road types are most likely to be supported by current and upcoming driving automation systems (Akamatsu et al., 2013). The field of view of the scenes was adjusted in accordance with the physical dimensions of the setup, resulting in an effective field of view with a horizontal viewing angle of 70 degrees.

All participants were exposed to all 6 scenes, which allows for observing any temporal effects that can occur after each successive trial. For instance, learning effects have been reported in the context of SA recovery after driving automation (Stanton & Young, 2000). Moreover, the consecutive exposure and measurement after each scene for each subject reduced the measurement error between subjects.



(a) Automated driving (b) Take-over alarm

Figure 3.3: Screenshots of a simulated driving video scene. In the left-bottom corner the HMI display with augmented driving information is located. The TOR message is displayed in the middle-bottom. The secondary task video clip is displayed in the bottom-right corner. The entire remaining area shows the driving scene.

3.4.2 Secondary task

During HAD, participants were instructed to pay attention to a secondary task. The task consisted of watching an informative video clip in the bottom right corner of the computer screen (see figure 3.3). The video clips consisted of fragments of the television documentary series ”How It’s Made”, season 24, episodes 12 and 13 (Hoss, 2014). Participants were quizzed after each trial about some visual contents of the video clip to motivate to focus on the video clip.

The secondary task simulated the ability to attend other things than the driving task. Consequently, it manipulated participants into a uniform mental state before regaining SA and therefore reducing variance across participants in SA questionnaire answering scores. The video clips were selected to not contain material that could potentially elicit strong emotions or attitudes. Moreover, the fragments contained rich visual scenes that required focus to attend all details and allowed for diverse quiz questions.

3.4.3 Human-Machine Interface augmentation

Participants in the experimental subject group were presented with an HMI which augmented driving information during the TOR. The HMI display was positioned in the left-bottom corner of the computer screen (see figure 3.3). During each scene the HMI presented two information elements concerning the driving situation during the transfer of control. An information element could be, for instance, a collision warning sign or a speed limit indication. Information elements were displayed using National traffic sign design conventions. The information applied to the driving situation for the immediate future.

The HMI display position choice was based on automotive design conventions. That is, for a left steering wheel position, driving-related information is presented on the left side and other, non-driving-related information is typically presented on the right side from the the driver’s view (Kern & Schmidt, 2009).

National traffic sign design conventions have been adhered for the visual design of the information elements. This is in line with used design of related works (Feenstra et al., 2009; McDonald, 2016). The use of existing and familiar design conventions for such information messaging accounts for interpretation and legibility. See McDonald (2016) for more discussion and consideration of driving situation message design. See appendix A for a specific overview of the information and the design of the HMI augmented information elements for each scene.

3.4.4 Take Over Request

The clips included a notification of the start of the TOR with an alarm sound and a salient ”TAKE OVER” textual message (see figure 3.3b). From the onset of the notification, the period of the TOR consistently lasted five seconds for all scenes before the clip ended and the SA questionnaire was started.

The TOR alarm was intended to consistently interrupt participants from attending the secondary task and shift their attention towards the driving task, i.e. starting to recover SA. A redundant, audiovisual alarm message, was chosen for being known for effective high workload task interruption (S. Lu et al., 2013). The alarm sounded for 820 ms, starting on the TOR onset.

The TOR period was based on a number of previous studies that investigated the effects of TOR period on the level of recovered SA (Gold et al., 2013; Mok et al., 2015; van den Beukel & van der Voort, 2013; Vlakveld & Hulleman, 2016; Zeeb, Buchner & Schrauf, 2015). They report on varying ranges of take-over times, from 0.5 seconds to 8 seconds, with inconsistent implications on SA or driving performance. An explanation for these discrepancies could be the wide range of experiment characteristics, such as simulated driving characteristics, secondary task type, and driving skills of participants (Zeeb et al., 2015). The current study is aimed to investigate a contrast in recovered SA based on two TOR scenarios (with vs without HMI augmentation). To expose this contrast the TOR period to recover SA must arguably be challenging but not impossible. Based on previous work with the most similar characteristics (Gold et al., 2013; Mok et al., 2015) and their findings, a TOR period of five seconds was implemented. Trial runs before the actual experiment took place confirmed a limited but possible recovery of SA by three volunteering participants. That is, all three volunteers partially answered SA questions correctly.

Driving scene, secondary task and augmented display all were integrated into a single stimulus video clip using video editing software. Car interior driving noise was added for realism.

3.5 Measures

3.5.1 Situation awareness

After the TOR the driving scene ended, after which the SA questionnaire was administered. The questions assessed the SA a participant had developed during the TOR. Some SA questions were related to elements that were retrievable exclusively from the driving scene, while other SA questions related to elements that were retrievable from both the driving scene as well as from augmentation by the HMI. SA questions were either labelled with corresponding type 'non-augmented' or 'augmented' respectively. Note that this question labelling was also done for the control group, which was not able to use the HMI augmentation.

This method of measuring SA was based on the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988b), which has been used before in similar studies (McDonald, 2016; van den Beukel & van der Voort, 2013). Measuring driving performance parameters such as reaction time, steering wheel usage or braking may not be a direct derivative of level of SA (van den Beukel & van der Voort, 2013). The SAGAT method has been validated in many studies and measures SA directly (Salmon et al., 2006). A requirement for using the SAGAT method is the interruption of the driving task, which resulted in the interruption of the driving simulation after the TOR in the current experiment. Moreover, to prevent working memory decay after interruption of the task, measuring HMI immediately after task interruption is imperative (Endsley, 2000). This was addressed by administering the HMI questionnaire immediately after driving simulation interruption and the briefing request to quickly answer the questions.

The questions were partially based on McDonald (2016), who developed a SAGAT questionnaire for the driving task. The questionnaire was adapted to the present experiment in order to apply it specifically to the current driving scenes. That is, the SAGAT questions queried about specific elements such as weather conditions, road characteristics, characteristics of the scenery, traffic conditions, and so on. Not applying SAGAT questions to the specific driving situation could fail to capture HMI with regard to driving safety aspects (van den Beukel & van der Voort, 2013).

Because of the emphasis on driving safety, the measured HMI of the questions was at level 1 and level 2 (Matthews et al., 2001), which was further discussed in the literature review chapter (see chapter 2). For example, a level 1 question was "Were any other road vehicles noticeable currently?" and a level 2 question was "What current obstacle could cause a safety problem?". Although some questions occurred after multiple scenes, repetition was limited to prevent learning behaviour. See appendix A for a specification of the HMI questionnaire after each scene. Each HMI question included an "I don't know" answer option and during the briefing participants were urged to use this option when they could not answer the question, instead of making a guess. This was done to minimize unjustified correct answers.

3.5.2 Secondary task quiz

After each scene, after the HMI questionnaire was administered, a second questionnaire was administered. This second questionnaire quizzed the participant about the secondary task video clip that was shown previously during the period of HAD.

This secondary task quiz was aimed to motivate participants to pay attention to the informative video clip during HAD, i.e. to be distracted from the driving task. The quiz questions referred to visual elements that were shown during the informative video clips, which enforced the participants to look at the informative video clip in order to answer the questions correctly. Similar to the HMI questionnaire, each quiz question included an "Unknown" answer option to minimize unjustified correct answers.

The answering data of this questionnaire were scored for correctness and was used to check for successful manipulation by the secondary task. That is, extremely low answer scores would suggest little attention was paid to the informative video clip, hence distraction from the driving task was unsuccessful.

3.5.3 Eye tracking

Participants' gazing direction was recorded during the entire simulation using an eye tracking system. Eye gazing data was aggregated into a number of metrics, which were calculated separately for each driving scene video area: the secondary task display, the HMI display and the driving scene. For the HAD phase metrics indicated the total duration each area was attended. For the TOR phase similar visit duration metrics were calculated, as well as the time of the first gaze to each area.

The HAD-phase secondary task display visit duration measurement was used as a secondary task distraction manipulation check. That is, a limited visit duration of the secondary task display indicated that a participant was not distracted sufficiently by the secondary task. The visit duration metrics of the TOR phase could indicate how much time each of the video areas was gazed at. In this way, for the subjects in the experimental condition, the relative attention spent on the driving situation compared to the HMI display for HMI recovery could be assessed.

3.6 Procedure

An experimenter received and registered the participants before the experiment. The participant read and signed an informed consent, which informed the participant about the general procedure, their ability to stop participation at any time and the ethical code of the Dutch Institute for Psychologists to which the experiment adheres.

Next, the participants were offered to take a seat at the experiment setup (see figure 3.2). Due to eye tracker physical requirements, the participants were instructed to not move their seat and remain in an upright upper body posture for the entire experiment, after which the experimenter administered the eye tracking calibration procedure. All briefing instructions, stimulus presentations and questionnaires were administered automatically using a stimulus presentation system. As such, the experimenter instructed the participant to thereafter follow instructions on the screen an started the experiment using the stimulus presentation system.

During the briefing participants were introduced with the experiment purpose and procedure. Next, a HAD scene, the secondary task and the TOR were introduced sequentially. The experimental group was introduced additionally with the HMI display, other briefing contents were similar. See appendix B for specific briefing contents. After the briefing, demographic information was gathered about gender, age and driving experience using a questionnaire. After completion of this questionnaire the actual experiment started.

The actual experiment took place in 6 trials during which participants were exposed to all 6 driving scenes. Each trial consisted of four phases:

1. HAD: Participants were exposed to a simulated driving scene but had been instructed to perform the secondary task of paying attention to the informative video clip, located in the right bottom corner of the computer display (see figure 3.3a).

2. TOR: An alarm briefly sounded and the textual message "TAKE OVER" was displayed, indicating the start of the TOR. Participants had been instructed to immediately start to pay attention to the driving scene in order to prepare to take over manual control of the car (see figure 3.3b). The TOR lasted five seconds.

3. HMI measurement: The computer screen turned blank and a questionnaire was administered, which measured the HMI that the participant had developed during the TOR.

4. Secondary task quiz: After HMI measurement another questionnaire was administered, which quizzed the participant about visual contents of the secondary task informative video clip that had been shown.

After all 6 trials had taken place the experiment ended. Participants were paid 5 Euro (7 Euro for participants that needed to travel to the laboratory) after completion of the experiment. The experimenter shortly debriefed the participant about the general purpose of the experiment.

3.7 Data processing

To allow analysis of questionnaires, all HMI- and secondary task quiz answers were scored. Consequently, proportion of correct HMI questions resembled the HMI level a subject had developed during TOR. The labels of HMI questions (i.e. non-augmented or augmented) allowed for creating HMI levels for two HMI element groups: elements that were only retrievable from the driving scene and elements that were retrievable from both the driving scene as well as from HMI augmentation.

Moreover, the questionnaire answers were transformed from scene reference to trial reference to allow analysis of temporal effects, by reversing the Latin square transformation.

Chapter 4

Results

4.1 Outlier analysis

Before performing analyses of the hypothesized effects, the measured data was reviewed to check for appropriateness. The descriptive statistics for the situation awareness (SA) question answering scores are presented in table 4.1. These statistics show that SA questionnaires from all scenes have been scored correctly on intermediate levels. This is also the case for participants: no participant had scored extremely high or extremely low on average. All SA answer data were therefore considered appropriate for further analysis.

SA question score		**min**	**max**	**$\bar{x}$**	**s**
Driving scene	Correct	.44	.73	.63	.11
	Incorrect	.13	.34	.22	.07
	"Unknown"	.07	.22	.14	.05
Participant	Correct	.37	.87	.63	.11
	Incorrect	.1	.47	.22	.08
	"Unknown"	.03	.3	.14	.08

Table 4.1: Descriptive statistics for SA question score. The "Driving scene" group shows the statistics for the average question score levels per scene. For example, the scene with the lowest average correct answers was correctly scored 44% on average. The "Participant" group shows the statistics for the average question score levels per participant.

With regard to the eye tracking data, the eye tracking system failed to capture eye gazing entirely for one participant. Moreover, for a large portion of the participants, the eye tracking system did not capture all eye gazing during the experiment. That is, for on average 12 participants, below 80% of eye gazing was captured during a trial. Because of the compromised validity, the eye tracking data was considered with caution and its use was excluded from the secondary task manipulation check. Moreover, eye tracking data was not used for further exploration of attention strategies that participants exhibited during the take-over request (TOR).

4.2 Effect of human-machine interface augmentation on level of recovered situation awareness

The main goal of the current study is to investigate the effect of human-machine interface (HMI) augmentation on the SA that is recovered during a TOR after a period of highly automated driving (HAD). To do so a comparison of level of SA (as measured by SA questionnaire) was made with and without the ability to use HMI augmentation during a TOR, hence the respective experimental- and control subject groups. Moreover, for each driving scene certain SA questions concerned SA elements that were only obtainable from the driving scene itself while other SA questions concerned SA elements that were additionally displayed on the HMI. The SA questions were labelled and grouped accordingly and allowed for a comparison of SA levels of both SA element groups, relative to the subject condition.

In figure 4.1 the separate mean SA levels are shown for both subject conditions and for both SA element groups. No main effect of HMI augmentation on the total recovered SA level was found ($F(1,48) = 3.230$, $p = .079$), although the mean recovered SA level was higher for the experimental group ($M = .65$, $SD = .13$) compared to the control group ($M = .61$, $SD = .1$). A significant interaction effect was found between HMI augmentation and SA element group on the recovered SA level ($F(1,48) = 11.211$, $p = .002$). This means that the difference in SA level between SA element groups was significantly different between subject conditions.

A following simple effect analysis using one-tailed t-tests revealed a significant difference between subject conditions for the SA level of the augmented SA element group ($t(48) = -3.365$, $p < .001$), where the experimental subject group recovered a higher level of SA during the TOR regarding the augmented SA element group. Moreover, although the experimental subject group recovered a lower mean level of SA during the TOR regarding the non-augmented SA element group, no significant effect was found ($t(48) = 0.573$, $p = .285$).

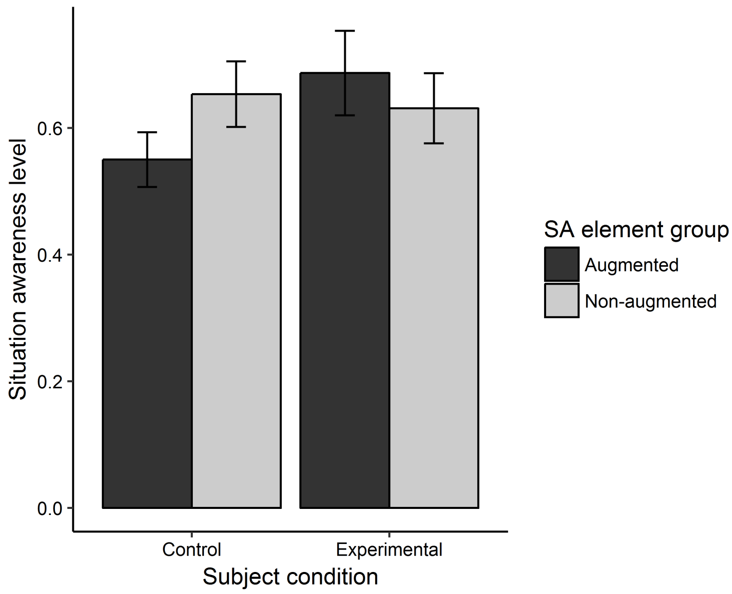


Figure 4.1: Level of recovered SA for experimental conditions and SA element groups

4.3 Secondary task manipulation

The answering data of the secondary task questionnaire was assessed to check whether participants were distracted from the driving task by paying attention to the secondary task. Given the visual nature of the quiz questions an unsuccessful secondary task manipulation was expected to result in extremely low answering scores. The descriptive statistics of the resulting secondary task answering scores are presented in table 4.2.

The statistics show a rather consistent degree of question difficulty between scenes, which suggests that questions from all scenes were rather challenging to answer. The participant answering statistics show a rather high mean scoring range (i.e. mean correct answer score varied between 22% and 89%). Nevertheless, all measured answering scores were deemed appropriate for successful manipulation, given the expected answering difficulties when no distraction was caused.

Secondary task question score		min	max	x̄	s
Driving scene	Correct	.46	.87	.64	.15
	Incorrect	.06	.23	.15	.08
	"Unknown"	.07	.37	.21	.12
Participant	Correct	.22	.89	.64	.16
	Incorrect	0	.44	.15	.1
	"Unknown"	0	.56	.21	.11

Table 4.2: Descriptive statistics for secondary task question score. The "Driving scene" group shows the statistics for the average question score per scene. For example, the scene with the lowest average correct answers was correctly scored 46% on average. The "Participant" group shows the statistics for the average question score per participant.

4.4 Explorations

4.4.1 Demographics

Explorative analyses on relations of demographical data and the level of recovered SA have been performed.

Age and level of recovered SA have a strong negative correlation, $r(48)$ = -.544, p < .001. Experience and level of recovered SA have a similar but slightly less strong correlation, $r(48)$ = -.471, p < .001. Correlations with the experience variable can, however, be affected by the coarse variable recoding. That is, due to stimulus presentation system constraints, a limited experience answer options range was offered to participants. These correlations show that younger participants, while less experienced, do show a better ability in regaining SA compared to older participants. No significant correlation exists between participants' gender and level of recovered SA ($r(48)$= .196, p = .174).

4.4.2 Temporal effects

The experiment design of 6 consecutive trials allowed for an exploration into temporal effects that could have occurred.

In figure 4.2 the mean recovered SA levels are shown for each trial. The mean level of recovered SA for each trial differed between .57 and .67 (M = .63, SD = .03). Specifically, an upwards trend is noticeable in the first trials and the last trial is downwards from the previous trials. A contrast analysis with a quadratic contrast to model the rising and falling slopes between the trial mean SA levels revealed to be significant (F(1,245) = 4.664, p = .032).

In figure 4.3 the mean relative visit duration during HAD of the secondary task display are shown for each trial. Based on the eye tracking data, these data show the mean time participants spent paying attention to the secondary task display during HAD, compared to other areas on the computer screen. The trial data suggest a negative trend towards paying less attention to the secondary task, contrary to prior instructions, and therefore paying more attention to the driving situation. A significant negative effect was found between trial number and distraction, using Greenhouse-Geisser correction (F(5,235) = 3.629, p = .009).

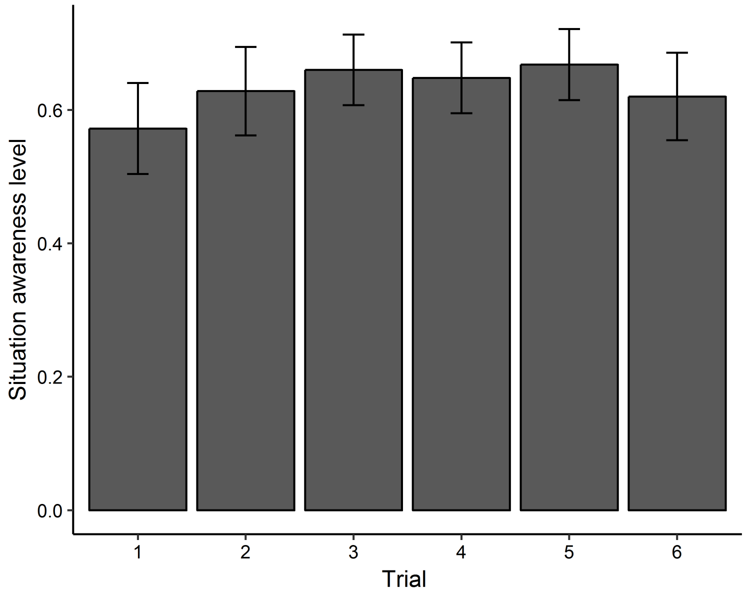


Figure 4.2: Mean level of recovered SA for each trial

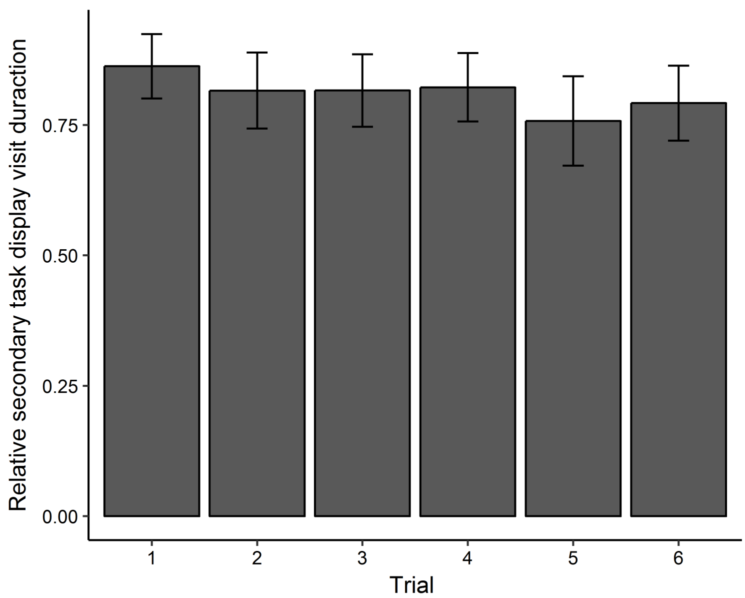


Figure 4.3: Relative visit duration of secondary task display during HAD for each trial

Chapter 5

Discussion

5.1 Effect of human-machine interface augmentation on level of recovered situation awareness

The current study is based on the hypothesis that, in the situation of an unannounced take-over request (TOR) from highly automated driving (HAD) to manual driving, the use of human-machine interface (HMI) augmentation results in an improved level of recovered situation awareness (SA) regarding elements that were augmented and a diminished level of recovered SA regarding elements that were only perceivable from the driving scene.

This hypothesis was tested using a passive driving simulator experiment. Participants were repeatedly exposed to virtual driving scenes where a TOR occurred. The experimental subject group was supported in the recovery of SA by an HMI, which augmented relevant driving information on a display during the TOR. The control subject group did not receive this support. After a five-second TOR period a questionnaire was administered that measured the level of SA that participants had been able to recover to. The questions were grouped according to whether they regarded information elements that were only available from the driving scene, or whether they regarded information elements that were additionally available through the HMI augmentation. The experiment therefore has a two-level between-subject design, where 'experimental condition' is the between-subject factor. The dependent variable is SA, represented by the score of correctly answered questions of the SA questionnaire.

Analysis showed a significant interaction between experimental subjects groups and the SA element group on measured level of recovered SA. Specifically, relative to the non-augmented SA element group, the experimental subject group was able to recover a higher level of SA for the augmented element group than the control group. No main effect of subject group on general level of recovered SA was found. Simple effect analyses showed a significant higher level of recovered SA of augmented elements for the experimental subject group and no significant effect but a lower mean SA level was found regarding the non-augmented elements. In other words, the results from the experiment show an advantage for recovering SA using HMI augmentation only for a part of the information that concerns the SA of the driving task, while the results also suggest a disadvantage for recovering SA that is not supported by HMI augmentation.

The results therefore partially support the hypothesis. The HMI augmentation did significantly increase one aspect (augmented elements) of SA while the other aspect (non-augmented elements) of SA was decreased but not significantly. Moreover, the overall level of SA was not affected significantly by HMI augmentation.

5.2 Explorations

In the results section (chapter 4), temporal effects of trial number on mean recovered SA levels have been explored. Specifically, an upward trend is noticeable in the first trials and the last trial is downwards from the previous trials. From related work it was expected that learning effects would cause an initial upward trend in SA level (Stanton & Young, 2000). The final downward trend in SA level could be caused by prolonged high workload due to the nature of the tasks involved in the experiment: a number of participants reported informally about the experiment being "intense" and "burdensome" This suggests the presence of a fatigue effect.

A significant negative effect was found between trial number and distraction as measured, using the eye tracker, by the time participants gazed at the secondary task display. The trial data show a negative trend towards paying less attention to the secondary task, contrary to prior instructions, and therefore paying more attention to the driving situation. This trend towards 'keeping an eye' on the road is in line with earlier work that has shown prioritizing visual attention behaviour in a driving context (Horrey et al., 2006).

A strong negative relationship was detected between participants' age and the mean recovered level of SA, meaning that older participants performed worse in recovering SA compared to younger participants. The negative effect of age on driving task performance that involved divided attention has already been established (Brouwer, Waterink, Van Wolffelaar & Rothengatter, 1991). Given the strong effect of age one could question the validity of the findings of the current study. However, both subject groups have a similar age distribution (see chapter 3), which accounts for age effects between groups. Moreover, the differential analysis of two SA measurement values (i.e. augmented and non-augmented SA element groups) for each participant accounts for individual differences within the subject groups.

5.3 Reflection on method design

The experiment design of 6 consecutive trials in which a TOR after HAD took place enabled the investigation of temporal effects that could take place. Specifically, learning effects from coping with multiple TOR's and therefore multiple occasions to demonstrate SA recovery were of interest. Explorations of temporal effects yielded a discovery of suggested a learning effect and a suggested fatigue effect. Moreover, multiple trials allowed for an exposure to varying driving scenes and corresponding driving situations, which therefore generalized the findings over a wider range of driving experiences. Resemblance to TOR that is conceivable as a real-life is limited, however. That is, the driving scenes demonstrated a period of HAD of not more than two minutes and prior instructions gave clear expectations of such a TOR to occur.

The use of a passive driving simulator setup has been deemed appropriate for the nature of the experiments such as the current (Martens & Fox, 2007). However, it is also acknowledged that the sensation of a possible real driving hazard cannot be evoked using a passive simulator and perhaps any simulator (Underwood, Crundall & Chapman, 2011). Given the explorative nature of the current study the passive driving simulator setup is therefore considered justified, even for the assessment of driving performance (Mayhew et al., 2011). For future studies that seek to validate the current findings in a more realistic environment, however, an interactive driving simulator with a higher degree of immersion is considered appropriate (Underwood et al., 2011).

To measure the level of SA that was recovered after the TOR the Situation Awareness Global Assessment Technique (SAGAT) was employed. Despite the central concept that SA has in the field of human factors (HF) and its implications the concept has in the field of automation of task execution, direct measurement of SA is not the most common method of choice in studies that consider the implications of SA in the scenario of a TOR after a period of HAD. Rather, the majority of such studies turn to measurement of driving performance metrics and subsequently derive effects on SA (Z. Lu et al., 2016; De Winter et al., 2014; Vlakveld, 2016), despite the limited validity they may have (van den Beukel & van der Voort, 2013). For exposing effects of HMI augmentation on SA the SAGAT method was deemed appropriate in the current study. The direct measurement of information elements a participant was or was not aware of yielded a contrast that was considerably in line with the hypothesis, as was discussed before. Moreover, SAGAT has been validated already in many domains of automation (Wickens, 2008). Therefore, the SAGAT method seems appropriate for further studies concerning HMI augmentation in SA support. One limitation of SAGAT, however, is the requirement of scene interruption for administering a questionnaire. Studies aimed at a more continuous exposure of a driving situation might therefore turn to online SA measurement (Gugerty, 2011). That is, SA measurement methods that do not require task interruption.

The main concern of the current study is the effect that driving task automation has on SA regarding the driving task. Generally, automation affects SA through three phenomena: change in vigilance and complacency in monitoring, a passive instead of active role in the control of the system at hand and change in feedback by the system to the operator (Endsley, 1996). To realistically simulate driving automation to affect SA such a simulation should arguably aim to affect these phenomena. Considering the current study, change in vigilance and complacency are argued to have been successfully manipulated. That is, distraction from the driving task by means of performing a secondary task enforced participants to exhibit complacency of the driving scene. The role a participant was able to obtain can be considered rather passive entirely, meaning that participants were not able to interact with the simulations and therefore obtained observing role. Briefing instructions attempted to immerse participants into the driving situation (see appendix B for briefing details). Similarly, feedback of the system could be considered of artificial nature as well. HAD as well as the TOR possessed limited realism to a real-world situation, where interaction with the vehicle and immersion as a whole is fundamentally different. In line with before, this limitation argues for an experimental design with higher ecological validity. Such a study could validate the current findings, which are based on a method design that allowed for limited realism.

5.4 Addressing need for investigating HMI augmentation as situation support strategy

Matthews et al. suggested that conveying driving information originating from an automated driving system can improve the SA of drivers (2001). However, they also discussed the potential negative implications offering such information may have by compromising the ability to paying attention to the actual driving scene for maintaining complete SA, similar to Tufano (1997). Recent discussions concerning control transfer from automated driving add to the need of further research in HMI for recovery of SA (Creaser & Fitch, 2015). It was argued that the HMI can have a crucial role in updating, maintaining and recovering the SA. Here as well potential side effects of employing an HMI were identified, specifically the additional effort of information comprehension and deciding on appropriate alert response were recognized as potential new distractions. In the current study these implications of augmenting driving information during a TOR have been investigated. The SA measurements in the experiment show a two-sided influence of HMI augmentation on recovered SA. The experimental subject group showed clear, significant improvements in level of SA concerning the SA elements conveyed by HMI augmentation. However, results also suggest diminished SA recovery for elements only obtainable from the driving scene, although this effect was not significant. The current study in this sense provides new empirical evidence about order of magnitude of the relative costs and benefits of HMI augmentation as a SA recovery support strategy. That is, the current study suggests costs of lowered SA in some areas (i.e. non-augmented SA) to be relatively low compared to the benefits that HMI augmentation can have in other areas concerning the awareness for the driving task (i.e. augmented SA), which showed a clear enrichment.

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Appendix A

Driving scenes

	Scene	Total duration	Augmented information
1	accident	0:33.000	Speed limit (130), Heavy traffic
2	highway slow car	1:12.00	Heavy traffic, Collision
3	jaywalking	2:09.300	Fog, Children crossing
4	merging	0:18.000	Speed limit (130), Heavy traffic
5	pedestrian and oil	1:16.000	Children crossing, Only middle lane (90)
6	fallen tree	0:49.500	Animals crossing, accident area

Table A.1: Scene characteristics in terms of scene duration and augmented information elements

A.1 Scene 1

Figure A.1: Screenshot of moment of take-over request (TOR) of scene 1. Multiple cars have passed by in the left lane. At the moment of TOR a truck is parked in the emergency lane, a car is stopped in the lane of the driver's view.

Situation Awareness Global Assessment Technique (SAGAT) questions:

- What is the current speed limit? Choose unknown if you did not notice. (80 km/h,100 km/h,120 km/h,130 km/h,Unknown)
- Were any other road vehicles noticeable? Choose unknown if you did not notice. (A car, A truck, Multiple cars and a truck, Unknown)

- What was the weather condition? Choose unknown if you did not notice. (Clear sky,Fog,Rain showers,Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Pedestrian, Vehicle ahead, No obstacle could cause a problem, Road debris, Unknown)
- What area surrounded the current road? Choose unknown if you did not notice. (Open fields, Forrest, City, Unknown)

A.2 Scene 2

Figure A.2: Screenshot of moment of TOR of scene 2. Multiple cars have passed by in the left lane and from the opposite direction. At the moment of TOR the headway of a car in front of the driver's view is getting dangerously close.

SAGAT questions:

- Were any other road vehicles noticeable currently? Choose unknown if you did not notice. (A car, A three cars, More than three cars, Unknown)
- What was displayed on the road sign on the right side of the road? Choose unknown if you did not notice. (A gas station company logo, A car dealer company logo, A TU/e logo, Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Road debris,Vehicle ahead,No obstable could cause a problem,Pedestrian,Unknown)
- What was the current shape of the road? Choose unknown if you did not notice. (Straight ahead,Curving to the left,Curving to the right,Unknown)
- How many default lanes did the current road have in your direction? Choose unknown if you did not notice. (One lane,Two lanes,Three lanes,Unknown)

A.3 Scene 3

SAGAT questions:

- What was the current speed limit? Choose unknown if you did not notice. (80 km/h,100 km/h,120 km/h,130 km/h,Unknown)

Figure A.3: Screenshot of moment of TOR of scene 3. A relative long route has been driven, including a road exit and entry of another road. At the moment of TOR a line of parked vehicles is parked, including a crowd of people.

- What was the weather condition? Choose unknown if you did not notice. (Clear sky,Fog,Rain showers,Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Pedestrian,Vehicle ahead,Road debris,No obstacle could cause a problem,Unknown)
- What object was visible on the left roadside? Choose unknown if you did not notice. (A house,Trees,An office building,No objects visible,Unknown)
- What was the current shape of the road? Choose unknown if you did not notice. (Straight ahead,Curving to the left,Curving to the right,Unknown)

A.4 Scene 4

Figure A.4: Screenshot of moment of TOR of scene 4. After a relative short drive a merge into a highway takes place but the lane is taken by trucks. At the moment of TOR the merge lane is about to end.

SAGAT questions:

- What was the weather condition? Choose unknown if you did not notice. (Clear sky,Fog,Rain showers,Unknown)
- How many default lanes did the current road have in your direction? Choose unknown if you did not notice. (One lane,Two lanes,Three lanes,Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Pedestrian on current lane,A truck in lane-to-merge,Road debris in lane-to-merge,No obstacle could cause a problem,Unknown)
- What kind of road vehicles did you notice? Choose unknown if you did not notice. (Only car(s),Car(s) and truck(s),Car(s) and truck(s) and motorcycle(s),Unknown)
- What was the current speed limit? Choose unknown if you did not notice. (80 km/h,100 km/h,120 km/h,130 km/h,Unknown)

A.5 Scene 5

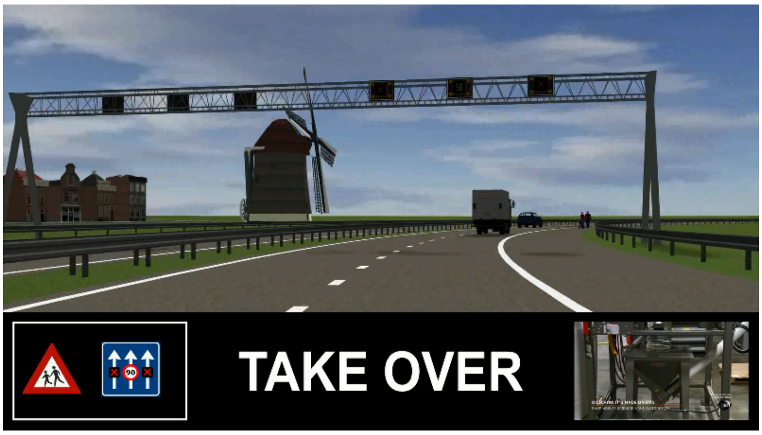

Figure A.5: Screenshot of moment of TOR of scene 5. Relatively mild traffic and a lead truck with salient scenery. At the moment of TOR matrix signs indicate only one lane available. Moreover, pedestrians can be noticed in the emergency lane, as well as a hard to notice oil mark on the driver's lane

SAGAT questions:

- Which road lanes were allowed to use? Choose unknown if you did not notice. (One lane: the current one,One lane: the left one,Two lanes,Unknown)
- What was the current speed limit? Choose unknown if you did not notice. (90 km/h,100 km/h,120 km/h,130 km/h,Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Pedestrian,Oil mark,Vehicle ahead,No obstacle could cause a problem,Unknown)
- What was the weather condition? Choose unknown if you did not notice. (Clear sky,Fog,Rain showers,Unknown)
- Was there any special building on the left side of the current road? Choose unknown if you did not notice. (An office building,A radio tower,A windmill,No special building,Unknown)

Figure A.6: Screenshot of moment of TOR of scene 6. Driving in the evening through a forest scenery with low traffic. At the moment of TOR a broken down car is at the side of the road with some people. Moreover, a hard to notice fallen tree is blocking the road ahead.

A.6 Scene 6

SAGAT questions:

- Based on the amount of daylight, what was the current time of the day? Choose unknown if you did not notice. (Morning,Afternoon,Evening,Unknown)
- What objects did you notice currently on the right side of the road? Choose unknown if you did not notice. (Reflector pole,Reflector pole and one pedestrian,Reflector pole and multiple pedestrians,Reflector pole and a car and multiple pedestrians,Unknown)
- Was there any reason to expect an animal crossing the road? Choose unknown if you did not notice. (Yes,No,Unknown)
- What current obstacle could cause a safety problem? Choose unknown if you did not notice. (Pedestrian,Vehicle ahead,No obstacle could cause a problem,A tree,Unknown)
- What was the current shape of the road? Choose unknown if you did not notice. (Straight ahead,Curving to the left,Curving to the right,Unknown)

Appendix B

Briefing instructions

The list below lists all briefing instructions that were presented to the participants before the experiment took place. Each item was displayed on the computer screen separately, participants could click on the computer mouse to continue to the next briefing item. See the method chapter (chapter 3) for further explanation.

1. Welcome to the automated driving experiment.

   Before the actual experiment starts you will be introduced to the purpose of the experiment and what is expected from you.

   Click the mouse to continue.

2. The purpose of this experiment is to understand what a car driver notices during failure of automated driving situations.

   Automated driving is a system functionality in which a driver does not need to control the car at all times. A driver can then spent time on other things and does not need to stay alert. Sometimes, however, this system can fail and the driver must take back control.

   In this experiment an automated driving situation is simulated. In the simulation the automated system fails and you must prepare to take back control. Your task is to prepare to take over control of the car by getting aware of the current driving situation, but only after the system alarms to take back control. Note that you do not have to actually take control of anything during the entire experiment: the task is to mentally prepare for taking control of a car.

   Your task will now be demonstrated in more detail. Note that this is still part of the introduction.

   Click the mouse to continue.

3. You will now be demonstrated what the automated driving situation looks like. Note that the automated driving system functions properly in this example and does not fail.

   After you continue the driving situation is demonstrated.

   Click the mouse to continue.

4. (A demonstration driving simulation scene was played for 16 seconds, excluding a secondary task informative video clip and TOR event)

5. You will now be demonstrated what a Take Over alarm looks like. During the experiment this Take Over alarm indicates that you need to prepare to take over control of the car.

   In other words, this is when you need to start paying attention to the driving situation.

   After you continue the Take Over alarm is demonstrated.

   Click the mouse to continue.

6. (A demonstration driving simulation scene was played for 16 seconds with a TOR event, excluding a secondary task informative video clip)

7. As mentioned before, you must start paying attention to the driving situation as soon as the Take Over alarm takes place. After the driving situation simulation has ended you need to answer a series of questions about things that you could have noticed.

   Answer the questions rather quickly, dont take more than 10 seconds to

   In total the experiment contains six driving situation simulations, which you will experience one by one.

   Click the mouse to continue.

8. As mentioned before, during reliable automated driving a driver can spend time on other things.

   In this experiment you spend time watching an informative video clip. Note that this is mandatory: you must pay attention to the video clip. You will be quizzed about the contents of the video clip afterwards.

   After you continue the informative video clip is demonstrated.

   Click the mouse to continue.

9. (A demonstration driving simulation scene was played for 16 seconds with a TOR event and including a secondary task informative video clip)

10. During the informative video clip you should have noticed several things. As mentioned before, during the experiment you will be quizzed about the video clip.

    The quiz will contain questions such as: 1. What kind of material was being worked at? 2. What was the color of the worker's clothes?

    Correct answers: 1: Metal 2: Green

    If you don't know the answer it is important that you choose the "I don't know" option. Do not make a random guess.

    Click the mouse to continue.

11. (This item was only presented to participants in the experimental subject group)

    To improve your preparation to take back control of the car a display will show a few icons that inform you about the driving situation during the Take Over alarm.

    You should use this display to better prepare yourself to take back control of the car. The information on this display should improve how well you answer questions about the driving situation after the simulation has ended.

    After you continue the support display is demonstrated.

    Click the mouse to continue.

12. (This item was only presented to participants in the experimental subject group)

    (A demonstration driving simulation scene was played for 16 seconds with a TOR event and including a secondary task informative video clip. During the TOR, human-machine interface (HMI) augmentation was active and two information elements were displayed)

13. This was the end of the introduction.

    After you continue some questions about you will be asked.

    Click the mouse to continue.

14. (The demographics questionnaire was administered)

15. Experiment starts now.

    Make sure you follow the instructions that were presented before.

    Summary of the instructions: - You must carefully follow the informative video clip in the first part of the simulation. You will be quizzed afterwards. - When a Take Over alarm takes place you must start paying attention to the driving situation. After the simulation has ended you will need to answer questions about what you could have noticed. - The experiment contains six driving situation simulations, which you will experience one by one. - Be completely honest in your answers: for the purpose of the experiment this is very important.

    Click the mouse to start the first driving situation simulation.