Unnecessary Alarms in Driving:

The Impact of Discrepancies between Human and Machine Situation Awareness on Drivers’ Perception and Behaviour

Inaugural-Dissertation
zur Erlangung der Doktorwürde der
Fakultät für Humanwissenschaften der
Julius-Maximilians-Universität Würzburg

Vorgelegt von
Christina Kaß
aus Mainz

Würzburg 2019

Erstgutachter: Prof. Dr. Wilfried Kunde

Zweitgutachter: Prof. Dr. Tanja Bipp

Tag des Kolloquiums: 11.11.2019

Danksagung

Ich bedanke mich aufrichtig bei Herrn Prof. Dr. Wilfried Kunde für die Betreuung dieser Doktorarbeit. Die regelmäßigen Treffen zu allen Phasen dieser Arbeit, die durch konstruktive Diskussionen und wertvolle Denkanstöße geprägt waren, haben mir sehr geholfen. Er hat mich dabei unterstützt, kognitive Psychologie und Verkehrspsychologie ganzheitlich zu betrachten und zusammenzuführen. Ich bedanke mich außerdem bei Frau Prof. Dr. Tanja Bipp und Herrn Prof. Dr. Lynn Huestegge für das Interesse an meiner Arbeit.

Diese Arbeit entstand während meiner Zeit als Doktorandin bei der Opel Automobile GmbH. Ich bedanke mich ganz besonders bei meinem Betreuer Prof. Dr. Gerald Schmidt, der eine riesengroße Unterstützung bei der Erstellung dieser Arbeit war. Die wertvollen Diskussionen und seine Erfahrung und Expertise haben mir dabei geholfen, neue Ideen zu generieren, Ergebnisse kritisch zu beleuchten und zu neuen Erkenntnissen zu gelangen. Darüber hinaus haben mir die „Psycho-Meetings“ mit Dr. Bernhard Wandtner, Henning Kienast, Anna Paetzold und Dr. Lena Rittger bei methodischen und inhaltlichen Fragen riesig geholfen. Die Arbeit und die Meetings mit euch haben außerdem immer viel Spaß gemacht.

Ich möchte mich für die Unterstützung meiner Kollegen der Abteilung EE Advanced Technology bedanken, besonders bei Dr. Nikolas Wagner für das Ermöglichen dieser Arbeit und seinen Rückhalt und bei Dr. Stefan Berger für das detaillierte Korrekturlesen. Ein besonderer Dank geht an meine Doktoranden-Kollegen, die für mich eine Bereicherung des Arbeitsalltags waren, Sven Hallerbach, Dr. Maximilian Harr, David Augustin, Jeremias Schucker, Florian Jomrich, Dr. Boliang Yi, Dr. Tobias Rückelt und Dr. Jens Ferdinand. Außerdem bedanke ich mich bei Leandra Schneider, Klaus Eckhard und Olaf Preuß vom Human Factors Center für die Unterstützung bei meinen Fahrsimulatorstudien.

Mein Dank geht an die (ehemaligen) Studentinnen Felicitas Muth, Diana Adrian, Clara Beck und Stefanie Brons, die mich in vielerlei Hinsicht bei meiner Arbeit unterstützt haben.

Außerdem war die fachliche Unterstützung von Dr. Norbert Schneider vom Würzburger Institut für Verkehrswissenschaften eine große Bereicherung für diese Arbeit. Vielen Dank!

Mein größter Dank geht an meine Eltern, Freunde, Anna und Robin. Danke, dass ich immer auf eure Unterstützung zählen kann und ihr jederzeit hinter mir steht.

Executive Summary

Forward Collision Alarms (FCA) intend to signal hazardous traffic situations and the need for an immediate corrective driver response. However, data of naturalistic driving studies revealed that approximately the half of all alarms activated by conventional FCA systems represented unnecessary alarms. In these situations, the alarm activation was correct according to the implemented algorithm, whereas the alarms led to no or only minimal driver responses. Psychological research can make an important contribution to understand drivers' needs when interacting with driver assistance systems.

The overarching objective of this thesis was to gain a systematic understanding of psychological factors and processes that influence drivers' perceived need for assistance in potential collision situations. To elucidate under which conditions drivers perceive alarms as unnecessary, a theoretical framework of drivers' subjective alarm evaluation was developed. A further goal was to investigate the impact of unnecessary alarms on drivers' responses and acceptance. Four driving simulator studies were carried out to examine the outlined research questions.

In line with the hypotheses derived from the theoretical framework, the results suggest that drivers' perceived need for assistance is determined by their retrospective subjective hazard perception. While predictions of conventional FCA systems are exclusively based on physical measurements resulting in a time to collision, human drivers additionally consider their own manoeuvre intentions and those attributed to other road users to anticipate the further course of a potentially critical situation. When drivers anticipate a dissolving outcome of a potential conflict, they perceive the situation as less hazardous than the system. Based on this discrepancy, the system would activate an alarm, while drivers' perceived need for assistance is low. To sum up, the described factors and processes cause drivers to perceive certain alarms as unnecessary. Although drivers accept unnecessary alarms less than useful alarms, unnecessary alarms do not reduce their overall system acceptance. While unnecessary alarms cause moderate driver responses in the short term, the intensity of responses decrease with multiple exposures to unnecessary alarms. However, overall, effects of unnecessary alarms on drivers' alarm responses and acceptance seem to be rather uncritical.

This thesis provides insights into human factors that explain when FCAs are perceived as unnecessary. These factors might contribute to design FCA systems tailored to drivers' needs.

Zusammenfassung

Kollisionswarnungen sollen Fahrer auf gefährliche Situationen aufmerksam machen und ihnen die Notwendigkeit einer sofortigen Reaktion signalisieren. Feldstudien zeigten jedoch, dass etwa die Hälfte aller Warnungen, die von herkömmlichen Kollisionswarnsystemen ausgegeben wurden, als unnötig einzustufen sind. Diese Warnungen wurden zwar auf Grundlage des implementierten Algorithmus korrekterweise aktiviert, allerdings führten sie zu keinen oder nur geringen Fahrerreaktionen. Psychologische Forschung kann einen wichtigen Beitrag zum Verständnis des tatsächlichen Assistenzbedarfs der Fahrer im Umgang mit Fahrerassistenzsystemen leisten.

Die vorliegende Arbeit untersuchte psychologische Faktoren und Prozesse, die Einfluss auf den wahrgenommenen Assistenzbedarf des Fahrers in potenziellen Kollisionssituationen haben. Um Bedingungen identifizieren zu können, unter denen Fahrer Warnungen als unnötig bewerten, wurde ein theoretisches Rahmenmodell entwickelt. Des Weiteren wurden die Auswirkungen unnötiger Warnungen auf die Reaktionen und die Akzeptanz der Fahrer untersucht. In diesem Rahmen wurden vier Fahrsimulatorstudien durchgeführt.

Die Ergebnisse zeigten, dass der wahrgenommene Assistenzbedarf der Fahrer durch ihre subjektive Gefahrenwahrnehmung vorhergesagt wird. Während das System den weiteren Verlauf einer potenziell gefährlichen Situation ausschließlich anhand physikalischer Messungen vorhersagt, berücksichtigen Fahrer zusätzlich ihre eigenen Manöverintentionen und Intentionen, die sie anderen Verkehrsteilnehmern zuschreiben. Wenn Fahrer vorhersagen können, dass sich der potenzielle Konflikt im weiteren Verlauf auflösen wird, bewerten sie die Situation ungefährlicher als das System. Eine solche Diskrepanz führt dazu, dass das System eine Warnung ausgibt, obwohl der Assistenzbedarf des Fahrers gering ist. Dadurch wird die Warnung als unnötig bewertet. Darüber hinaus ist die Akzeptanz für unnötige Warnungen geringer als für nützliche, wobei dies keine Auswirkungen auf die Gesamtakzeptanz eines Kollisionswarnsystems hat. Während Fahrer zunächst moderat auf unnötige Warnungen reagieren, wird die Intensität ihrer Reaktionen mit wiederholtem Erleben unnötiger Warnungen geringer. Insgesamt scheinen die Auswirkungen unnötiger Alarme auf die Alarmreaktionen und die Akzeptanz der Fahrer jedoch eher unkritisch zu sein. Die Ergebnisse erklären, durch welche menschlichen Faktoren Fahrer Kollisionswarnungen als unnötig wahrnehmen. Diese Faktoren können dazu beitragen, Warnungen an den tatsächlichen Assistenzbedarf der Fahrer anzupassen.

Table of Contents

1 Introduction

Forward Collision Alarm (FCA) systems aim to intercept driver errors by providing assistance if necessary. Activated alarms serve to signal a hazardous situation and the need for an immediate corrective driver reaction (International Organization for Standardization, 2016). Alarm activation of conventional FCA systems depends on physical measurements, more precisely on the time to collision (TTC) criterion. These strategies were initially developed for the worst-case scenario in which the driver is visually distracted and, thus, at risk to miss a hazardous situation. Under this condition, previous research has repeatedly shown that alarms activated by low TTC values had a positive impact on driver performance in imminent collision situations (e.g. Lee, McGehee, Brown, & Reyes, 2002; Lees & Lee, 2007). However, under naturalistic driving conditions, only approximately 50 % of all FCAs activated by predefined TTC values were useful (Flannagan et al., 2016; General Motors Corporation, 2005). These alarms were associated with a high braking response rate and triggered in predefined use cases for preventing rear-end collisions, such as approaching a stopped or braking lead vehicle. In contrast, the other half of FCAs resulted in no or only minimal driver responses. In these situations, the alarm was still activated by a present other vehicle in the same lane. Therefore, the alarm activation was correct according to the implemented algorithm. It is assumed that drivers perceived these alarms as unnecessary as they seem to have deliberately refrained from responding to the alarm. Importantly, the absence of driver responses did not cause collisions. Following a definition by Lees and Lee (2007), these alarms can be categorized as *unnecessary alarms*.

These findings demonstrate that alarm activation strategies of conventional FCA systems do not always seem to meet drivers' actual need for assistance. Previous research already aimed to address this problem by developing adaptive assistance systems that either suppressed certain alarms, adapted the alarm timing, or alarm design dependent on different adaption parameters, such as visual attention (e.g. Brouwer & Hoedemaeker, 2005; Hammoud, Smith, Dufour, Bakowski, & Witt, 2008). However, the selection of adaption parameters was simply based on their hypothesised impact on drivers' need for assistance. Therefore, it is important to take a step back and to examine drivers' actual need for assistance. Even though the investigation of effects of FCA systems and their alarm design on driver performance represents a broad field of human factors research since many years, a systematic understanding of psychological factors and processes that determine drivers' actual need for assistance in potential collision situations is still lacking. Moreover, previous research has not yet systematically investigated the effects of unnecessary alarms on driver responses and their acceptance. This knowledge would be important to assess the potentially detrimental effects of unnecessary alarms and the importance of implementing new alarm activation strategies. There are no consistent data that show under which conditions unnecessary alarms lead to driver acceptance or annoyance (e.g. Naujoks, Kiesel, & Neukum, 2016; Nodine, Lam, Stevens, Razo, & Najm, 2011). Additionally, results of driving simulator studies and naturalistic driving studies provided different results concerning the impact of unnecessary alarms on the intensity of driver responses (e.g. Flannagan et al., 2016; Lees & Lee, 2007).

The overarching objective of this thesis was to examine which psychological factors and processes influence drivers' perceived need for assistance in potential collision situations. To address this research question, a theoretical framework of drivers' subjective alarm evaluation was developed that compares human and system situation awareness and evaluation. The framework served to derive the corresponding hypotheses (Figure 3-1). It was hypothesised that drivers' perceived need for assistance would be predicted by their retrospective subjective hazard perception. Accordingly, unnecessary alarms were assumed to result from situations judged as critical by the system, while perceived as non-hazardous by the driver. The theoretical framework further suggested that discrepancies between system risk assessment and drivers' subjective hazard perception would result from advantages of the drivers' situation awareness over the system. In addition, this thesis aimed to provide insights into drivers' acceptance of unnecessary alarms. A further goal was to investigate the impact of unnecessary alarms on driver responses. It was assumed that drivers' prior experiences with unnecessary alarms and their ability to anticipate the further course of the situation might influence the intensity of alarm responses. Four driving simulator studies were carried out to examine the outlined research questions.

2 Theoretical Background

This chapter provides an overview of previous research and theoretical concepts that address the challenge of providing driver assistance adapted to drivers' needs. To understand the demands and cognitive components of unassisted manual driving from a psychological perspective, Section 2.1 introduces driver models and the construct of situation awareness with the involved cognitive processes. Section 2.2 focuses on requirements for and the effectiveness of driver assistance systems, and more specifically alarm systems. To elucidate the difficulty of alarm systems to reliably discriminate between hazardous and non-hazardous events, Section 2.3 refers to the signal detection theory. In this context, the meaning of unnecessary alarms is introduced. Furthermore, this section collects empirical research that investigated the effects of unnecessary and false alarms on driver behaviour and drivers' subjective evaluations. Section 2.4 addresses adaptive assistance systems that offer an approach to increase perceived system reliability by aiming to reduce the rate of unnecessary alarms.

2.1 The Manual Driving Task

Driving can be considered as a goal-oriented and complex task consisting of several subtasks with varying demands (McRuer, Allen, Weir, & Klein, 1977). Drivers need to decide which route to take, steer and accelerate, and to be constantly aware of the environment. Additionally, they have to react quickly to changes in the environment to avoid collisions with other road users. To understand under which circumstances humans could benefit from system support while driving, this section delineates the demands of manual driving by introducing two popular driver models and the construct of situation awareness.

2.1.1 Driver Behaviour Models

To describe human behaviour in driving and the involved psychological processes, driver models typically divide the driving task into hierarchical levels that differ according to their demands and available time frames.

Rasmussen (1983) proposed three levels of behaviour on which human operators perform goal-directed behaviour when interacting with technical systems. Task performance on the three levels demands different levels of attentional control. At the lowest level, skill-based behaviour represents sensory-motor actions that people perform automatically without conscious control, e.g. shifting gears or lane keeping. Demanding medium attentional control, rule-based behaviour is oriented towards a certain goal and controlled by a set of rules that have proven successful previously, e.g. when drivers change the lane or turn at an intersection. On the highest conceptual level, knowledge-based behaviour applies to unfamiliar situations where no rules from previous encounters are available. To develop a useful plan, this goal-controlled behaviour requires conscious attentional control and effort. The three levels interact with each other and are not distinct. Thus, a task can require more than just one level.

Michon (1985) proposed to divide the driving task into three hierarchical levels that differ according to the required level of control and the available time frame for task duration. The three levels are hierarchical in the sense that they influence each other in a top-down way. On the strategic (or planning) level, the driver performs the long-term planning of the driving trip that requires complex mental processes to evaluate involved costs and risks. For example, the driver needs to determine the destination of the trip and which route to take. The tactical (or manoeuvring) level includes controlled action patterns to attain the goals that were set on the strategic level. In a limited time frame of some seconds, drivers plan and execute driving manoeuvres such as turning, overtaking, and obstacle avoidance. On the operational (or control) level, drivers execute automatic action patterns which are controlled in milliseconds. This level includes subtasks where drivers automatically control the vehicle in response to the environment, such as steering, handling the clutch, and other interactions with vehicle controls.

Table 2-1

Relation of the Driver Models by Michon (1985) and Rasmussen (1983) with Examples (Adapted from Hale, Stoop, Hommels, 1990)

Michon **Rasmussen**	**Strategic**	**Tactical**	**Operational**
Knowledge-based	Navigating in unfamiliar area	Controlling a skid	Novice in first lesson
Rule-based	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill-based	Daily driving route	Negotiating familiar intersection	Vehicle control in a curve

Table 2-1 shows that the two models can be related to each other in a matrix (Hale, Stoop, & Hommels, 1990). One dimension represents the three levels of the driving task related to the time frame for task duration (Michon, 1985) and the other dimension represents the three levels of behaviour that differ according to their demands (Rasmussen, 1983). Experienced drivers usually perform strategic tasks with knowledge-based, tactical tasks with rule-based, and operational tasks with skill-based behaviour. However, novice drivers without much driving experience still need conscious control to carry out sensory-motor actions. Hence, they initially perform operational tasks on a knowledge-based level (upper right cell in Table 2-1). Additionally, drivers might not be able to perform tactical tasks in non-routine situations on a rule-based level if there are no available rules from previous encounters. Thus, such situations require knowledge-based behaviour to compare different action alternatives and select the most appropriate response.

It is assumed that collision avoidance, in general, takes place on the tactical and operational level with skill-based and rule-based behaviour. Oriented towards the goal of collision avoidance, drivers need to apply certain learned rules (rule-based behaviour) to anticipate an impeding conflict and to trigger the decision for an appropriate driving manoeuvre on the tactical level. To carry out the corresponding manoeuvre, operational tasks such as braking and steering are performed automatically on a skill-based level without conscious control. Morando, Victor, and Dozza (2016) identified two visual cues that help drivers to anticipate a lead vehicle conflict in manual driving. The first cue is the brake light onset that informs the driver that the lead vehicle started braking. However, this cue does not contain information about the intensity of the braking manoeuvre. The second cue is visual looming that is referred to as the optical expansion of the lead vehicle in the eye of the driver. Looming objects represent salient visual stimuli that are associated with behavioural urgency and induce automatic and reflexive reactions (skill-based behaviour) (Regan & Vincent, 1995). If drivers fail to anticipate an impeding critical situation based on these cues, Morando et al. (2016) found that FCAs could serve as an effective mechanism to orient drivers' attention to the impeding conflict. In addition to the visual cues in the traffic environment, visual-auditory alarms can complement the detection of impeding conflicts by appealing to the auditory sense for relaying information to drivers. Thus, alarms have the potential to support drivers in performing the complex manual driving task.

However, prior studies showed that a combination of the cues brake light onset, visual looming, and FCA did not always trigger strong braking responses as automated stimulus reaction patterns (Flannagan et al., 2016; General Motors Corporation, 2005). In these situations, additional action-relevant cues might have suppressed rules for performing a collision avoidance manoeuvre and, thus, suppressed automatically activated sensory-motor actions such as strong braking. Instead, these cues might have activated alternative rules that did not result in braking responses, e.g. changing lanes or turning. Section 2.3.4 discusses these scenarios in more detail.

The driver models by Michon (1985) and Rasmussen (1983) provide an overview of the structure of the driving task and required levels of attentional control. To describe and understand the process that leads to decision-making and action performance in dynamic traffic environments, the following section introduces the construct of situation awareness with the involved cognitive processes.

2.1.2 Situation Awareness and Involved Cognitive Processes

Safe driving requires the correct processing of a high number of stimuli resulting in appropriate response decisions with regard to navigation, manoeuvering, or vehicle control. Human information processing models describe the psychological processes involved in the driving task (Wickens, Hollands, Banbury, & Parasuraman, 2013). Drivers use their senses, in particular the visual system, to process relevant elements in the environment. To extract meaningful events and objects from the sensory input, selective attention is required. The further processing of attended information can require different levels of cognitive processing. In some situations, drivers can use well-learned reaction patterns performed automatically without conscious control (skill-based behaviour; Rasmussen, 1983). More complex situations require deeper cognitive processing. In this phase, drivers use prior knowledge stored in long-term memory to comprehend the meaning of the perceived elements with regard to their current goals and predict future actions of these elements (rule- or knowledge-based level; Rasmussen, 1983). Drivers then select and execute an action, such as steering or braking. Changes in the environment caused by drivers' actions, in turn, create new patterns of information to be sensed.

A construct that describes and integrates the different cognitive processes involved in interacting with technical systems in dynamic environments is referred to as situation awareness. Endsley (1988) defined situation awareness 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” (p. 97). Figure 2-1 shows the three levels of situation awareness. On the first level, drivers use their senses to perceive the status, attributes, and dynamics of relevant elements in the traffic environment, such as the position or acceleration of other vehicles (perception level). On the basis of the perceived elements, drivers use prior knowledge to form a holistic comprehension of the current situation by interpreting and combining these elements in the light of their current goals (comprehension level). For example, drivers comprehend the meaning of red traffic lights. Based on the conscious processing of elements in the situation, drivers are usually able to predict future events and dynamics, e.g. their own subsequent actions or those of other road users (projection level). This ability allows for the recognition of events a couple of seconds ahead and helps drivers to decide on the most favourable course of action to meet their current goals. Throughout this thesis, the term “anticipation” will be used to refer to “projection” as it is the more common term in the psychological context (e.g. Hoffmann, 2009; Kunde, Koch, & Hoffmann, 2004; Muhrer & Vollrath, 2011; Schmidt, 2012; Stahl, Donmez, & Jamieson, 2014). As illustrated in Figure 2-1, Endsley (1988) understands decision-making and action performance as two separate stages that directly proceed from situation awareness. Similar to information processing models, Endsley (1988) proposed a feedback loop between action performance and the state in the environment. The performance of actions results in changes in the environment and, thus, a changed status of relevant elements perceived by the driver. As traffic situations are highly dynamic, drivers must constantly adjust their situation awareness.

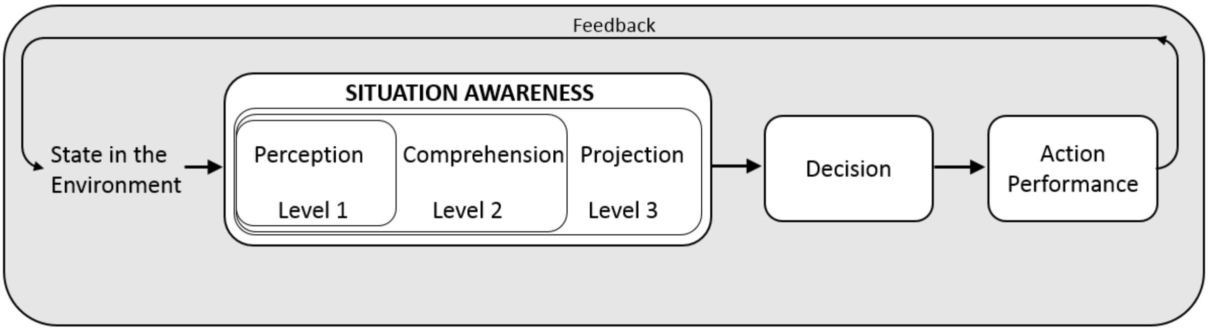

Figure 2-1. Situation awareness model by Endsley (adapted from Endsley, 1988).

Endsley (2000) emphasises the importance of temporal aspects for situation awareness. The temporal dynamics of a situation require drivers to comprehend and predict how soon a certain element will influence their goals and tasks. They need to understand how much time is available until a certain event occurs or a particular action needs to be performed.

Situation awareness has its roots in human factors research in the field of aviation, but has also been transferred to the driving context (e.g. Gugerty, 1997, 2011; Rauch, 2009). In contrast to car drivers, pilots do not perceive most of the relevant elements directly from the environment, but via a remote interface.

The three levels of situation awareness, decision-making, and action performance are influenced by cognitive processes which are described in the following paragraphs.

2.1.2.1 Attention

On the perception and comprehension levels, attention allows drivers to selectively attend only to that information that is important for their current goals and tasks. Lamme (2000) describes attention “as a set of mechanisms that enable the better routing of sensory inputs towards the executive systems of the brain” (p. 399). To be able to act in dynamically changing environments, attention needs to be guided by both top-down and bottom-up mechanisms. Shinoda, Hayhoe, and Shrivastava (2001) argued that the “visual system must balance the selectivity of ongoing task-specific computations against the need to remain responsive to novel and unpredictable visual input that may change the task agenda” (p. 3536). Bottom-up mechanisms describe an involuntary shift of attention to salient visual stimuli such as red braking lights of the lead vehicle (e.g. Connor, Egeth, & Yantis, 2004). Top-down mechanisms can direct drivers’ attention voluntarily to environmental elements that are relevant for their current goals and tasks (e.g. Connor et al., 2004). Expectations that are based on schemata stored in long-term memory influence this selection (see also Section 2.1.2.3). With regard to top-down mechanisms, Gugerty (1997) has found that drivers focused their attention more on vehicles in front of them than to those behind them or farther away. The focus of attention seemed to reflect the meaning of these elements concerning drivers’ goals of safe driving. However, the sensorial perception of a stimulus does not necessarily result in conscious perception. Drivers need to cognitively process the meaning of perceived stimuli. Attention determines the selective processing of incoming sensory information. Following the driver models by Michon (1985) and Rasmussen (1983), the processing of perceived elements when executing operational tasks would require less attentional control (skill-based behaviour) than tactical or even strategic driving tasks (rule-based or knowledge-based behaviour). Endsley (1988) also addressed the role of *automaticity* as a mechanism to overcome temporary problems of limited attentional control.

2.1.2.2 *Working Memory*

Working memory, and more specifically the central executive, is involved in the process of constructing, maintaining, and updating situation awareness (Baddeley & Hitch, 1974; Baumann, Petzoldt, Groenewoud, Hogema, & Krems, 2008; Endsley, 1988). Perceived elements are stored, processed, and kept available in working memory. On the comprehension level, working memory resources are necessary to combine these elements with existing knowledge. On the anticipation level, the working memory serves to integrate the perceived elements into the prediction of their future status. This cognitive process is highly demanding on working memory. When driving tasks require higher levels of attentional control, working memory is hypothesised to be the bottleneck for situation awareness (Endsley, 1988; Fracker, 1988).

2.1.2.3 *Long-term Memory*

Schemata influence all levels of situation awareness (Endsley, 1988). Schemata are cognitive structures in long-term memory that represent a person's knowledge and the characteristics of a certain field. Providing a framework to understand and predict traffic situations, schemata represent active organizations of drivers’ past experiences and reactions (Bartlett, 1932). Schemata can reduce the demand on working memory. On the perception level, expectations based on schemata help drivers to direct their attention only to currently relevant elements. On the comprehension level, certain trigger conditions activate schemata that are organized hierarchically. While higher levels only consist of basic characteristics of certain situations, lower levels include a higher amount of concrete characteristics. This enables drivers to identify stereotypical traffic situations. Using prior knowledge, drivers can integrate multiple and complex elements into a holistic comprehension of the situation. Additionally, these schemata allow drivers to form expectations about the probable development of the situation. Anticipation requires the recognition of stereotypical traffic situations that are likely to result in similar future developments from one time to another (Stahl et al., 2014).

2.1.2.4 *Intention*

Even when not further addressed by Endsley (1988), drivers’ action goals or rather intentions are assumed to have an important impact on situation awareness as well. Human intention is defined as “the overarching goal embedded in an action sequence” (Zunino et al., 2017, p. 591). Driving can be decomposed into various behavioural intentions. Intention is a mental state associated with the anticipation of future events and has a strong impact on drivers’ actions in the near future (Malle, Moses, & Baldwin, 2003). In psychology, there are different theories that aim to describe how intentions evolve and how they influence human behaviour. The parallel distributed processing model by McClelland and Rumelhart (1986) proposes that intentions trigger different reactions to the same stimulus. Cohen and Huston (1994) used this model to explain the Stroop task. Stroop (1935) instructed subjects to either read out a colour word (e.g, green, red) or to name the colour in which the words appeared. Colour identification has been demonstrated to be easier when the colour word and its colour stimulus are congruent than when they are incongruent. An incongruent stimulus induces two conflicting reaction tendencies that delay the selection of the correct reaction. Cohen and Huston (1994) propose two processing pathways between stimulus identification and action selection, one for word reading and one for colour naming. The processing of the two pathways is modulated by the activation of the currently intended behaviour (either word reading or colour naming). With regard to situation awareness in driving, drivers may draw more attention to stimuli that are relevant for their current intentions. Additionally, dependent on the current driver intention, the same environmental stimulus can result in different actions.

The ideomotor theory proposes that intentional actions are determined by anticipations of their own sensory effects, referred to as action-effect relations (e.g. Herbart, 1825; Hoffmann, 2009; James, 1890/1981; Kunde et al., 2004). In other words, before executing a certain action, the agent has a mental representation of the related action effects. The anticipation of action effects addresses the corresponding motor patterns and enables the agent to execute the action. Thus, intentional actions presuppose knowledge about the effects that can be attained by a certain action and sensory perceptions associated therewith, e.g. the proprioceptive perception of hand movements. The ideomotor theory is a conceptual framework for this learning process of action-effect relations.

It is assumed that drivers do not only consider their own manoeuvre intentions for anticipation, but also intentions attributed to other road users. People are able to infer others' intentions from action observations (Malle et al., 2003). The human ability to comprehend intentions and other mental states of other persons by relating observable actions to underlying mental states is referred to as *theory of mind* (Meltzoff, 1995; Premack & Woodruff, 1978). However, for anticipation in driving, drivers need to predict future actions of other road users *before* they are actually executed. In this context, it must be differentiated between *early activity recognition* and *intention prediction* (Zunino et al., 2017). Early activity recognition denotes the ability to recognize an action before it is fully disclosed as an online assessment of the initial part of the action. It requires the identification of details inherent to the current observations that would lead to a future action, e.g. recognizing a lateral movement as the initial part of a lane change (Simon & Bullinger, 2018; Zunino et al., 2017). Intention prediction describes the ability to anticipate another individual's unobserved future action prior to real time, e.g. predicting a lane change intention by turn indicator usage (Simon & Bullinger, 2018; Zunino et al., 2017). There are motion patterns that are specific of a certain subsequent action (Zunino et al., 2017). For example, the movement kinematics when a person reaches to grasp a bottle contain information of the future intention to either pour, displace, throw, or pass the bottle (Ansuini, Giosa, Turella, Altoè, & Castiello, 2008). A person who observes such movements senses early differences and is able to discriminate between movements performed with different intentions (Ansuini, Cavallo, Bertone, & Becchio, 2015). The human mirror neuron system enables persons to transform visual information into knowledge about others' intentions (Gallese & Goldman, 1998). Mirror neurons respond to biological movements performed by others. The activation of these neurons during the observation of an action executed by another person corresponds to the activation of the internal motor representation of the observed action (Bonini, Ferrari, & Fogassi, 2013). In other words, the observer mirrors the other's motor action by activating the corresponding motor representations in his or her brain. The activation of the same motor representations enables the observer to infer the other's underlying intention (Bonini et al., 2013). It has been found that certain mirror neurons show differential activity during the observation of reach-to grasp movements with different intentions (Bonini et al., 2010; Fogassi et al., 2005). Future action prediction is often supported by the scene context (Ansuini et al., 2015; Zunino et al., 2017). Therefore, people use their knowledge about possible actions associated with the environment in which the agent's motions are embedded. Kaplan and Iacoboni (2006) showed that there is a mirror neuron area that is sensitive to the congruency of contextual and kinematic cues. In a study by Simon and Bullinger (2018), drivers considered the context to predict lane changes of other vehicles. A visible reason like an obstacle or slower driver in the lane increased the probability to anticipate a lane change.

Even though drivers are often not able to directly observe movements of other *persons* in traffic, but of *vehicles* without the possibility to see the other human driver, they are presumably able to anticipate intentions of other road users by taking their actions, movements, and the context into account. Dependent on the consideration of drivers' own manoeuvre intentions and the anticipation of future actions of other road users, the same traffic constellation might result in different anticipations of future states.

2.1.3 Sources of Incorrect Situation Awareness in Driving

Situation awareness is seen as a crucial prerequisite for effective decision-making and execution of actions in dynamic traffic environments. The process to achieve a correct situation awareness, and to derive appropriate decisions and actions, is very demanding and contains error potential on different levels.

According to the task capability interface by Fuller (2000), drivers are at risk of making errors when current task demands exceed drivers' momentary capability. Capability refers to drivers' current ability to deliver their level of competence. While the current ability is influenced by states such as drowsiness, distraction, or motivation, the general level of competence depends on drivers' knowledge and skills gained through experience, education, and training. The following paragraphs describe how drivers' limited capabilities in combination with a certain level of task demand impair situation awareness and, thus, decision-making and action in driving.

Jones and Endsley (1996) used the aviation safety reporting system to analyse sources of 262 situation awareness errors made by pilots or controllers. When errors fit to more than one level of situation awareness, they were coded at the lowest level considering that errors on lower levels result in subsequent errors on higher levels. They found that 76.3 % of all errors in aviation were perception errors, 20.3 % were comprehension errors, and 3.4 % were anticipation errors. Additionally, results of a naturalistic driving study with more than 3,500 participants that lasted three years provided insights into factors that caused crashes and near-crashes by their impairing effect on situation awareness (Dingus et al., 2016). Near-crash signifies that there were observable factors that could have led to a crash, but the driver executed a successful evasive manoeuvre.

According to Jones and Endsley (1996), the majority of all errors on the perception level (and 35 % of all errors) were associated with "a failure to monitor or observe relevant data that were clearly present in the situation” (p. 509) mainly caused by distraction. In line with this finding, Dingus et al. (2016) reported that observable driver distraction had a high prevalence of 51.9 % and increased the overall crash risk by two times. Inappropriate visual search strategies due to incomplete or incorrect schemata represent another explanation for this error type. Prior research showed that experienced drivers fixated more often on environmental elements classified as potential hazards than unexperienced drivers (Falkmer & Gregersen, 2005; Lee et al., 2008). Other perception errors in aviation resulted from information that was needed but currently not available (example in driving: sight obstruction), elements that were hard to detect or discriminate (example in driving: bad visibility conditions), misperceptions (example in driving: misperception of curve radius), and memory loss (example in driving: forgetting the speed limit drivers had previously been aware of) (Jones & Endsley, 1996).

On the comprehension level, errors in aviation were found to be caused by incomplete or incorrect mental models (Jones & Endsley, 1996). Mental models represent knowledge structures that enable operators to understand and predict system states (Rouse & Morris, 1986). As pilots perceive the environment through the system and manual drivers perceive the environment directly with their senses, the term mental model needs to be replaced by the term schema. When transferring these errors types to manual driving, incorrect or incomplete schemata may lead to failures to integrate the perceived elements in the environment into a holistic understanding of the situation. Incorrect schemata can cause situations in which persons are not able to identify a relevant element as it seemed to be irrelevant in their schema (Jones & Endsley, 2000). With regard to incomplete schemata, experienced drivers have stored much more experiences with certain traffic constellations in long-term memory than novice drivers. Therefore, they have advantages to comprehend that a situation is or can become hazardous (Lee et al., 2008; Underwood, Ngai, & Underwood, 2013). Even if an appropriate schema is available, comprehension can be impaired by working memory limitations. Each task imposes mental workload on the limited information processing capacity (Wickens et al., 2013). When cognitively distracted, drivers assign cognitive resources to competing tasks and their remaining working memory capacity cannot afford to connect the perceived elements to prior knowledge (Baumann & Krems, 2007; Baumann et al., 2008). Apart from cognitive distraction, working memory capacity can be limited by drugs, alcohol, drowsiness, and strong emotions. Dingus et al. (2016) revealed that these variables increased the overall risk of a crash by five times. In situations with impaired capacity, drivers are not able to further process elements that they have perceived visually. This phenomenon is referred to as “looked-but-failed-to-see” (Simons, 2000).

Jones and Endsley (1996) found that a lack of schemata or incomplete schemata can lead to anticipation errors even if persons were able to perceive and comprehend the relevant elements in the environment. Prior research revealed the impact of driving experience on the ability to anticipate hazardous outcomes. Experienced drivers outperformed novice drivers in hazard anticipation and, thus, in adequately responding to hazards (Crundall, 2016; Garay-Vega & Fisher, 2005; Jackson, Chapman, & Crundall, 2009). Analogously to the comprehension level, cognitive distraction has a detrimental effect on drivers’ ability to anticipate the future development of the current traffic situation (Baumann et al., 2008; Mühl & Baumann, 2018; Muhrer & Vollrath, 2011).

It is possible that a person has developed an accurate situation awareness, but makes a poor decision or an action performance error nonetheless. In the study by Jones and Endsley (1996), 4 of 17 registered accidents were caused by decision errors. Dingus et al. (2016) referred to these errors as judgement errors such as aggressive driving, speeding, and tailgating with a prevalence of 4 % and an increased overall risk of a crash by 11 times.

Moreover, drivers who made a correct decision, can still fail to correctly execute the action. Even if errors in vehicle operation caused by inexperience with the vehicle or road way were very rare (0.07 %), they resulted in an overall crash risk increased by 204 times (Dingus et al., 2016).

Summarized, there are many different sources that can result in incorrect situation awareness. In turn, incorrect situation awareness can lead to negative consequences, such as collisions. In the driving context, advanced driver assistance systems (ADAS) have the potential to mitigate driver errors which can be caused on each stage of situation awareness.

2.2 Assisted Driving

This section provides an overview about the aims and functionalities of ADAS, focuses on alarms with their purposes and requirements, and reports on studies that demonstrated the effectiveness of alarms provided by reliably working ADAS.

2.2.1 Driver Assistance Systems

To improve safe and efficient driving, ADAS intend to intercept driver errors by providing support if necessary. They assist drivers with information, alarms, or take over a part or several parts of the driving task. Assistance means that drivers are supported by the system, but still need to execute the larger part of the driving task.

The international society of automotive engineers (SAE International) suggests six levels of driving automation (SAE International, 2018). On Levels 0 to 2, human drivers perform the entire dynamic driving task or parts of it. Thus, they need to monitor the driving environment while being supported by varying degrees of system support. Consequently, drivers need to remain attentive and retain responsibility. On Level 0 (no driving automation), drivers have to perform all aspects of the driving task while alarm or intervention systems provide momentary support during potentially hazardous situations. For example, collision avoidance systems activate an alarm if drivers are at risk to collide with another road user. When the collision becomes imminent, these systems are mostly able to brake autonomously without driver input. Furthermore, lane departure warning (LDW) systems warn the driver in case of unsafe lateral positions, while lane keep assistance systems actively intervene with subtle forces on the steering wheel. These systems interact with the driver to a high degree and, therefore, have an active impact on the processes involved in the driving task. On Level 1 (driver assistance), ADAS continuously either execute parts of the longitudinal (acceleration and deceleration) or of the lateral driving task (steering) while drivers have to permanently control the other parts of the driving task. For example, the adaptive cruise control feature continuously controls the longitudinal driving task. After drivers have set the desired speed, the system keeps a set following distance relative to the vehicle ahead by automatically adjusting the vehicle’s speed (International Organization for Standardization, 2002). While drivers are still responsible for steering, they are allowed to release the brake and accelerator pedals. On Level 2 (partial driving automation), one or more ADAS execute the lateral as well as the longitudinal driving task at the same time, e.g. the traffic jam assist. On Level 3 and above, automated driving system features perform the entire dynamic driving task, at least in a specific operational design domain. Thus, the system undertakes the monitoring task of the environment. Level 3 is referred to as conditional driving automation, Level 4 as high driving automation, and Level 5 as full driving automation. The development and realisation of automated driving functions precedes in large steps. However, vehicles with lower levels of automation will keep their place on the road for many further years.

Even if alarm systems are implemented to series vehicles since many years, there are still open questions and problems that need to be addressed from a human factors standpoint. As long as drivers are responsible to perform either the entire driving task or parts of it, human factors research remains an important topic for the development of ADAS. The consideration of users' needs when interacting with technological systems is one of the most relevant issues for system development (Cacciabue, 2007).

This thesis focuses on driver assistance on SAE Level 0, and more specifically on collision alarms. The following section elucidates the purposes of alarms and requirements for their effectiveness.

2.2.2 Alarms

According to Laughery and Wogalter (2006), warnings have the purposes …

… to make the world safer by improving health and reducing accidents and injuries,

… to provide information about hazard and potential negative consequences,

… to influence or control behaviour of the person to whom it is directed, and

… to serve as a reminder to call the hazard into awareness.

Warnings can be either static or dynamic (Laughery & Wogalter, 2006). Static warnings are constantly present and usually visual, such as warnings in product manuals and on medical packaging. Dynamic warnings are only triggered when a system detects a hazardous event in the environment. As traffic environments are highly dynamic, ADAS must provide dynamic warnings. According to the International Organization for Standardization (2016), ADAS are responsible for detecting hazardous events and notifying drivers of these external hazards (ISO 18682). The issued warning requests immediate evasive action. According to the taxonomy of emergency signal terms by Bliss and Gilson (1998), the term “alarm” seems to be more applicable to the field of ADAS than “warning”. While warnings provide information that a hazard may exist under certain circumstances, alarms indicate a hazardous situation at the present time and serve to take immediate corrective action to avoid negative consequences. Throughout this thesis, the term “alarm” will be used to refer to dynamic warnings.

An essential requirement for effective alarms is that they must be designed salient enough to capture attention, as people usually do not actively search for alarms (Bustamante, 2008; Laughery & Wogalter, 2006). With regard to the sensory modality of alarms, it has been found that reaction times are shorter and detection rates are higher with auditory and tactile stimuli than with visual stimuli (Hershenson, 1962; Sklar & Sarter, 1999). Results by Todd (1912) revealed that the reaction time to a primary (visual) stimulus paired with an accessory (auditory) stimulus was shorter than to the primary stimulus alone, even though participants were instructed not to respond to the accessory stimulus when it occurs alone. There are further evidences that a presentation of signals via two or more processing channels (multimodal presentation) speeds up reaction times compared to a single signal (Hershenson, 1962; Miller, 1982; Raab, 1962; Selcon, Taylor, & McKenna, 1995). This phenomenon is referred to as "redundancy gain" (e.g. Wickens, Prinet, Hutchins, Sarter, & Sebok, 2011) or "intersensory facilitation" (Hershenson, 1962) and can be explained in different ways. According to the assumption of separate activation, signals on different channels produce separate response activation processes. Redundant signals decrease the reaction time because one sensory modality may be processed faster than the other modality (Miller, 1982; Raab, 1962). Alternatively, coactivation models suggest that two or more signals jointly contribute to the process of producing a reaction (Miller, 1982). A study by Miller (1982) provided evidence for the coactivation assumption. Studies in the context of assisted driving also found positive effects of multimodal alarms on reaction time and response accuracy (Ho, Reed, & Spence, 2007; Liu & Jhuang, 2012; Reinmueller, Koehler, & Steinhauser, 2018). Furthermore, the physical intensity of an alarm, e.g. operationalised by acoustic parameters such as fundamental frequency or pitch range, or by visual parameters such as size and blink frequency, increases the receiver's perceived intensity, respectively urgency, and the alarm detection rate (e.g. Braun & Shaver, 1999; Edworthy, Loxley, & Dennis, 1991). The approach of matching the urgency conveyed by the alarm to the urgency of the indicated event has been also referred to as urgency mapping (Hellier & Edworthy, 1999). Perez, Kiefer, Haskins, and Hankey (2009) investigated the effectiveness of visual FCAs with different levels of visual intensity (operationalised by location, luminance, and size). Figure 2-2 illustrates the different types (left panel) and locations (right panel) of the tested visual alarms. Each alarm was flashed at 4 Hz. With regard to alarm detection time, results favoured the reflected Head-up Display (HUD) consisting of a strip of 10 horizontally aligned red light-emitting diodes (LEDs) positioned at the driver centreline (HUD-10 in Figure 2-2).

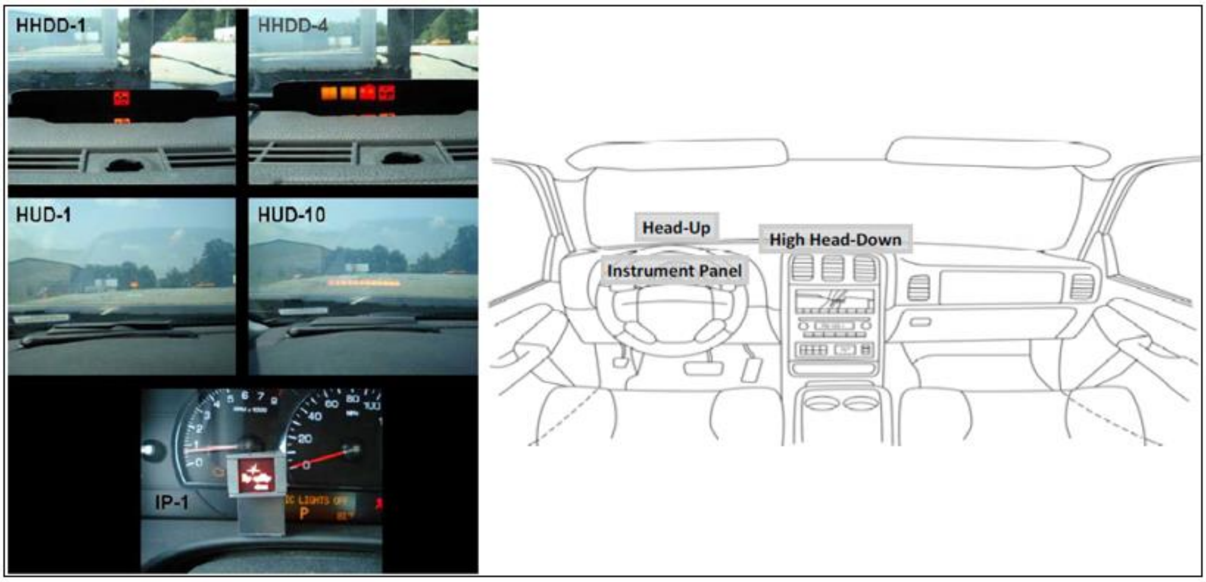

Figure 2-2. Close-up views of visual component of FCAs that were compared by Perez et al. (2009). HHDD = high head-down display positioned, HUD = Head-up display, IP = Instrument Panel. The numbers in the left panel reflect the number of consisting elements (e.g. LEDs).

A further requirement for alarms to be effective is their ability to detect hazardous events (Bustamante, 2008). In order to provide alarms in response to hazardous events, ADAS represent sensor-based systems that activate alarms when thresholds predefined by the system designer are violated (Bliss & Gilson, 1998). Within the alarm activation process, the ADAS has to sense, analyse, predict, and assess the risk of events in the environment as a basis for alarm activation. This process is illustrated on the left panel of Figure 3-1. On the sensing level, the ADAS uses its sensors (e.g. radio detection and ranging (radar), camera) to continuously monitor the environment around the vehicle, such as the distance to other road users and their velocity. Additionally, vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communication technology enable the system to be aware of upcoming changes in the environment that are not yet perceptible for the driver, e.g. an approaching vehicle at an intersection or a changing traffic light status. Concurrently, in-vehicle sensors measure the ego vehicle’s dynamic state (e.g. velocity and yaw rate) and input control information (e.g. steering wheel angle and pedal position). On the level of situation analysis, objects and parameters measured by different sensors are merged to a holistic representation of the situation. Based on the situation analysis, the system predicts a future status within the next few seconds (prediction level). FCA systems use the TTC criterion as physical measurement to predict the position of the ego vehicle in relation to other objects. The TTC represents the time required for two road users to collide if they remain on the same path at constant speed. It is calculated by the distance between two road users divided by their relative velocity (Janssen & Nilsson, 1991). In a situation with a decelerating lead vehicle, the so-called Enhanced TTC (ETTC) calculation additionally considers the relative deceleration (Winner, Hakuli, Lotz, & Singer, 2015). To assess the risk of the current situation, the system compares currently measured values to threshold values that system designers have predefined as critical. As soon as current values fall below predefined thresholds, the system evaluates the situation as critical. As a consequence, the system issues an alarm. Environmental events with identical physical measurements result in the same level of risk assessment every time they fall below a predefined threshold.

This section demonstrated that prior research has already clarified how to develop alarms that effectively attract drivers' attention and provoke quick reactions. Moreover, alarms must be associated with hazardous events. The following section provides an overview of the effectiveness of alarms provided by ADAS under the condition that the system was able to reliably detect an external hazard.

2.2.3 Effects of Alarms on Driving Performance

This section reports research results that provided insights into the circumstances under which drivers benefit from alarms provided by ADAS. In the reported studies, alarms were always associated with an actual hazardous event or, at least, with the instruction to immediately respond to the alarm. The findings are reported separately on the three levels of situation awareness (perception, comprehension, and anticipation).

In contrast to human perception, system sensing with sensors is independent of monitoring failures, such as visual distraction (see Section 2.1.3; Jones & Endsley, 1996). Additionally, V2X communication technology and radar sensors enable the system to sense upcoming changes in the environment that are not yet perceptible for the driver, e.g. due to sight obstructions or bad visibility conditions. Prior research has found that visually distracted drivers benefited from FCAs. Compared to non-assisted driving, FCAs reduced the number of collisions (Kramer, Cassavaugh, Horrey, Becic, & Mayhugh, 2007; Lee et al., 2002), the accelerator release time in response to a hazard (Kramer et al., 2007; Lees & Lee, 2007), and the collision velocity (Lee et al., 2002). Additionally, FCAs increased the safety margin to the lead vehicle in safety critical situations measured by headway and minimum TTC (Dingus et al., 1997; Lee et al., 2002; Maltz & Shinar, 2007). In some of the reported studies, alarms even improved driving performance in comparison to non-assisted driving when drivers were visually attentive (Kramer et al., 2007; Lee et al., 2002). Moreover, Naujoks, Grattenthaler, Neukum, Weidl, and Petrich (2015) found that alarms reduced the number of critical encounters with obstructed as well as with free view on the opposing road user compared to non-assisted driving. Concerning bad visibility conditions, alarms could increase safety margins to a lead vehicle in clear as well as in bad visibility conditions in comparison to non-assisted driving (Janssen & Thomas, 1997). In summary, alarms improved driver performance when the system had advantages over drivers' perception and also when drivers were able to perceive a hazardous event independently of the system.

In contrast to the system's situation analysis, human comprehension can be impaired by mistakes in cognitive processing caused by incomplete and incorrect schemata or cognitive distractions (see Section 2.1.3; Jones & Endsley, 1996). Reinmueller et al. (2018) found that drivers who were cognitively distracted by a passenger conversation reacted faster to multimodal alarms (vibrotactile-auditory) than to unimodal alarms (auditory-only). However, the same effect was found when drivers were not engaged in a passenger conversation. As there was no control group without assistance, the study did not provide knowledge if alarms improved the performance of cognitively distracted drivers compared to non-assisted driving. Stahl, Donmez, and Jamieson (2016) examined the effect of an assistance system that intended to support drivers' comprehension (conscious perception) of relevant environmental cues on driving performance of experienced and novice drivers. The system highlighted relevant cues and displayed a warning message on a display (e.g. "Slow Tractor Ahead!"). While the assistance had no impact on driving performance of experienced drivers, it improved performance of novice drivers compared to non-assisted driving. When being assisted by the system, the driving performance of novice drivers matched those of experienced drivers. Additionally, novice drivers rated the system to be more useful than experienced drivers. The findings suggested that only those drivers whose schemata were incomplete (novice drivers) benefited from the assistance. The assistance could not further increase the performance of experienced drivers as they already had well-developed schemata which enabled them to direct their attention to relevant cues and to process their meaning (see Section 2.1.2.3). To sum up, drivers benefited from driver assistance when the system had advantages over drivers' comprehension due to cognitive distraction and incomplete schemata. When drivers' comprehension was not impaired, the reported studies provided inconsistent results on the effectiveness of driver assistance.

While the system bases its prediction on physical measurements, human anticipation might be impaired by previous expectations that are not met in the current situation or by incorrect or incomplete schemata (see Section 2.1.3; Jones & Endsley, 1996). As long as drivers were able to anticipate conflict situations, Schmidt (2012) found that non-assisted drivers reacted as fast and as good as assisted drivers to a lead vehicle conflict. When the anticipation of an upcoming conflict was difficult because the conflict partner's behaviour contradicted drivers' initial expectations or the conflict suddenly arose without previous cues, alarms reduced reaction times and the frequency of safety critical encounters compared to non-assisted driving (Naujoks et al., 2015; Schmidt, 2012). The study by Stahl et al. (2016) (see previous paragraph) additionally examined the effect of an assistance system that intended to support drivers' anticipation of future developments on driving behaviour. Therefore, an interface displayed likely consequences of a certain event (e.g. "Slow Tractor Ahead! *Be aware of Braking Vehicles*!"). While the system improved the driving performance of novice drivers compared to non-assisted driving, it had no impact on performance of experienced drivers. With system support, the driving performance of novice drivers matched those of experienced drivers. Additionally, novice drivers rated the system to be more useful than experienced drivers. The results suggested that assistance could complement novice drivers' incomplete schemata about stereotypical traffic situations that allow for the anticipation of certain events in the near future. As these schemata of experienced drivers were already complete, their performance did not differ with and without assistance (see Section 2.1.2.3). Taken together, the results provide evidence that alarms improved driver performance when the system had advantages over drivers' anticipation. Alarms did not improve the performance of drivers who were able to anticipate an upcoming hazardous event themselves.

In conclusion, prior research showed that alarms improved driver performance when the system had advantages over drivers' perception, comprehension, or anticipation. However, drivers still benefited from alarms when they were able to perceive a hazardous event independently of the system. When drivers' comprehension was not impaired, two studies provided contradictory results concerning the effectiveness of driver assistance (Reinmueller et al., 2018; Stahl et al., 2016). Drivers who were able to anticipate an upcoming hazardous event themselves did not benefit from alarms (Schmidt, 2012; Stahl et al., 2016). The reported studies investigated the effectiveness of perfectly reliable alarm systems. However, the development of reliable alarm systems whose alarms are always associated with a real hazardous event is very challenging. The following section addresses this challenge and provides insights into the effects of unreliable systems on operators' alarm responses and their subjective evaluations.

2.3 Alarm Systems with Low Reliability

Given a perfectly reliable alarm system, alarms have a positive effect on driver performance. Ideally, systems should only activate alarms in presence of an actual hazard. However, present-day alarm activation algorithms are not perfectly reliable in detecting truly hazardous events. Section 2.3.1 refers to the signal detection theory to describe the alarm system's performance to discriminate between hazardous and non-hazardous events. Moreover, the following sections deal with the effects of perceived system reliability influenced by unnecessary and false alarms on drivers' behaviour and their subjective evaluations.

2.3.1 Signal Detection Theory

The Signal Detection Theory (SDT) can be utilized to describe the performance of an alarm system to discern between hazardous and non-hazardous events (Green & Swets, 1966). Originally, the SDT was developed to determine absolute thresholds with regard to questions of psychophysics. Later, this theory was applied to describe human sensory discrimination (Swets, 2014). The aim was to quantify sensory thresholds, more specifically the ability of a human to detect a signal (e.g. tone) embedded in noise (background interference). This ability is described by the sensitivity parameter d'. The human needs to set a response criterion along a probabilistic decision variable which is referred to as beta β. Dependent on the two parameters d' and β, there are four possible outcomes shown in the left panel of Figure 2-3. Correct responses represent either a hit when a present signal is detected or a correct rejection when an absent signal is not detected. Two types of errors may occur. A miss indicates the outcome when a present signal is not detected. A false alarm occurs when an absent signal is detected by mistake.

This theory can be applied to ADAS that need to detect hazardous events (signal-plus-noise) in non-hazardous normal conditions (noise-alone). This ability represents the sensitivity parameter *d′* of the classic SDT and depends basically on the sensor quality. Analogously to the original sensory discrimination task, a response criterion β must be set. In the context of alarm systems, “decision threshold” seems to be the more appropriate term. Human observers set their response criterion in accordance with perceptions of prior probabilities. In contrast, ADAS use decision thresholds that were pre-set by system designers. The performance of the alarm system (right panel of Figure 2-3) is dependent on the combination of the ability to detect a hazardous event (*d′*) and the decision threshold (β). A hit would be classified as an alarm associated with a hazardous driving situation. A correct rejection occurs when the system does not issue an alarm while no hazardous event takes place. The situation when sensors fail to detect a hazardous event and the system does not issue an alarm is referred to as a miss. Sources of this error type may be poor visibility caused by darkness or rain. False alarms are triggered in absence of a hazardous event and are usually activated by sensor noise or system malfunction without apparent trigger. Therefore, their activation is usually not comprehensible for drivers (Lees & Lee, 2007).

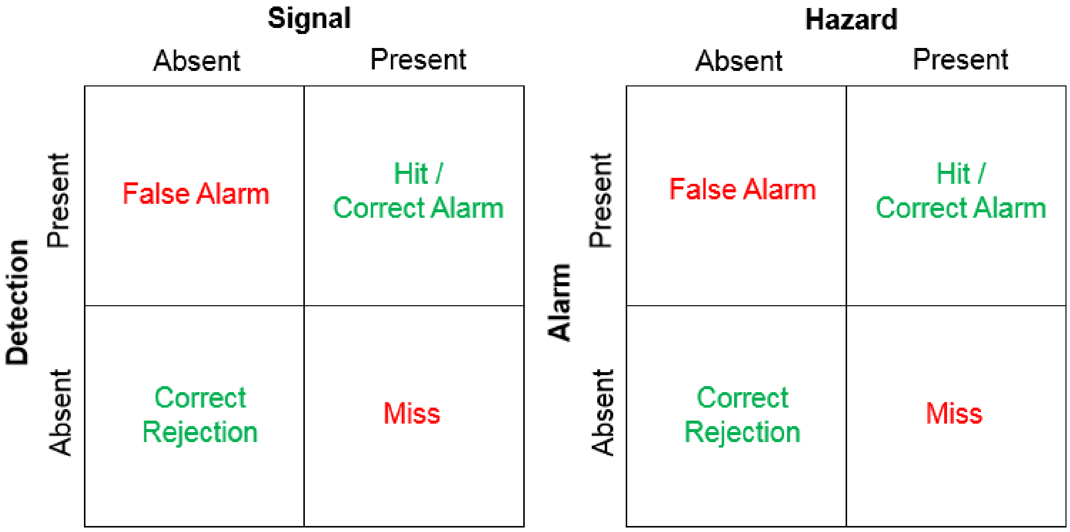

Figure 2-3. Classic signal detection theory used for human sensory discrimination (left) and hazard discrimination of ADAS (right).

Based on SDT, there exists a trade-off between misses and false alarms. When setting the decision threshold of an alarm system, the cost of a miss versus a false alarm needs to be considered (Parasuraman, Hancock, & Olofinboba, 1997). As no alarm system is perfectly reliable, system engineers have to decide which type of error is more tolerable. In a safety-related environment, misses are often considered to be more dangerous than false alarms (Lerner, Dekker, Steinberg, & Huey, 1996). For example, a smoke detector that fails to detect the smoke (miss) has much higher negative consequences than a smoke detector that triggers a false alarm. Abe, Itoh, and Tanaka (2002) showed that misses decrease system trust more seriously than false alarms. However, other studies revealed a detrimental effect of false alarms on performance during subsequent events (see Section 2.3.4). Therefore, some researchers have recommended avoiding false alarms with the same or even higher priority than misses (Chancey, Bliss, Liechty, & Proaps, 2016; Dixon, Wickens, & McCarley, 2007; Navarro et al., 2018). In practice, however, system designers tend to follow the so-called “engineering fail-safe approach” by setting the decision threshold of alarm systems low enough to alert operators of even the slightest possibility of a hazardous event (Swets, 1992). This approach leads to the problem that minimizing the probability of misses inevitably increases the probability of false alarms. High false alarm rates do not only result from a liberal decision threshold, but also from a low base rate of real-world hazardous events (Parasuraman et al., 1997). Farber and Paley (1993) estimated a base rate of 173 crashes for every million lead vehicle stops for freeway driving. According to data published by the German Federal Statistical Office (2017), there are about 12 million kilometres between two accidents involving personal injury on German motorways.

In terms of SDT, the *system reliability* represents the percentage of events that the system correctly identified as hazardous or non-hazardous. More specifically, it is defined by the relative proportion of hits and correct rejections out of all possible events (Wiczorek & Manzey, 2010). The alarm reliability is referred to as the “positive predictive value” and describes the probability that an alarm truly indicates a hazardous event (ratio of hits over all alarms; Getty, Swets, Pickett, & Gonthier, 1995). System reliability and the positive predictive value of an alarm decrease with an increasing number of false alarms. When talking about system reliability, it is necessary to discern between subjectively perceived and objective system reliability. The following section addresses this differentiation and introduces the meaning of unnecessary alarms.

2.3.2 Perceived System Reliability: Unnecessary Alarms

Based on the classical SDT, objective system reliability depends on the system's ability to correctly discriminate between hazardous and non-hazardous events and on the pre-set decision threshold. However, objective system reliability might diverge from operators' subjectively perceived system reliability (Sullivan, Tsimhoni, & Bogard, 2008). If operators believe that certain activated alarms occurred in absence of credible hazardous situations, their perceived system reliability might be low even though the alarm activation was correct according to the implemented system algorithm (Lerner et al., 1996; Sullivan et al., 2008). The system would classify these alarms as hits, while they are subjectively perceived as unnecessary by the human operator.

> *Unnecessary alarms* are "associated with a situation judged hazardous by the designer, but not by the driver. The driver can understand what triggered the alert" (Lees & Lee, 2007, p. 1267).

Unnecessary alarms could be caused by the system's sensitivity parameter *d'* as well as by its decision threshold β. Additional to the sensor quality, the sensitivity parameter depends on the parameters selected by the system designer to define a hazardous event. It is conceivable that drivers consider other or additional parameters than the system to detect a hazardous situation. Moreover, the system's decision threshold to activate alarms does not necessarily always match operators' decision criterion regarding hazardous events. Table 2-2 demonstrates that unnecessary alarms result from a mismatch between the system's and the driver's hazard classification and evaluation of activated alarms. While objective system reliability only takes *real* false alarm rates into account, operators' perceived system reliability considers false as well as unnecessary alarms.

Table 2-2

Comparison of Hazard Classification and Evaluation of Activated Alarms between System and Driver

System			**Driver**	
Hazard classification	**Alarm evaluation**		**Hazard classification**	**Alarm evaluation**
Event hazardous	Correct alarm	=	Event hazardous	Correct alarm
		≠	Event non-hazardous	Unnecessary alarm
Event non-hazardous	False alarm	≠	Event hazardous	Correct alarm
		=	Event non-hazardous	False alarm

The following paragraphs describe results of interview studies and naturalistic driving studies that provided insights into the prevalence of unnecessary collision alarms under naturalistic driving conditions.

In three different interview studies, owners of vehicles equipped with FCA systems were asked about their experiences. In a study by Braitman, McCartt, Zuby, and Singer (2010), 43 % of the 380 participants reported that they received FCAs perceived as false or unnecessary. The authors concluded that it was “clear that the systems sometimes warn when drivers do not think the warnings are necessary” (Braitman et al., 2010, p. 276). In another study, 37 % of the 155 respondents commented that they received FCAs while not perceiving a crash risk (Eichelberger & McCartt, 2014). Analysing interviews with 183 additional drivers, Eichelberger and McCartt (2016) found that the likelihood to perceive certain FCAs as unnecessary differed by driver age and gender. While 36 % of drivers younger than 41 years indicated having received unnecessary alarms, only 12 % of drivers older than 60 years made this experience. Men were more likely than women to indicate that they have perceived FCAs as unnecessary (21 % of male and 8 % of female participants). Additionally, 63 % of 108 participants who took part in a naturalistic driving study with an integrated FCA system reported that they received alarms when they did not need them (Nodine et al., 2011). A shortcoming of all studies was that it was not possible to determine how many of the mentioned alarms were, by definition, false or unnecessary.

A naturalistic driving study by General Motors Corporation (2005) analysed 137,000 miles of driving of 96 participants who used an FCA system over a period of 12 months. To understand system performance and drivers' alarm responses, the context surrounding imminent FCAs was classified into different scenarios. Results revealed that only 27 % of all FCAs could be categorized as useful correct alarms. In these situations, the lead vehicle decelerated or stopped and remained in the same lane as the ego vehicle. Drivers responded to these alarms with braking in 88 % of the time. According the definition by Lees and Lee (2007), 32 % of all FCAs could be roughly classified as unnecessary. In these situations, a lead vehicle has been present as apparent alarm trigger and the TTC fell below the alarm activation threshold. Thus, alarm activation was correct according to the implemented algorithm. However, the potential conflict usually dissolved through a divergence in the paths of the two involved vehicles. Shortly after the alarm has been activated, either the ego or the lead vehicle changed lanes or turned (Figure 2-4). Drivers braked in response to these alarms in only 30 % of the time. Most remaining alarms have been activated by roadside objects that did actually never lie in the path of the ego vehicle. These potential conflicts dissolved by lateral movements of the ego vehicle. According to Lees and Lee (2007), these alarms can be classified as nuisance alarms. In contrast to unnecessary alarms, nuisance alarms are not intended by the system designer and are typically triggered by out-of-path objects. In a focus group that was executed after study participation, participants frequently reported that they received more FCAs than they believed were truly necessary.

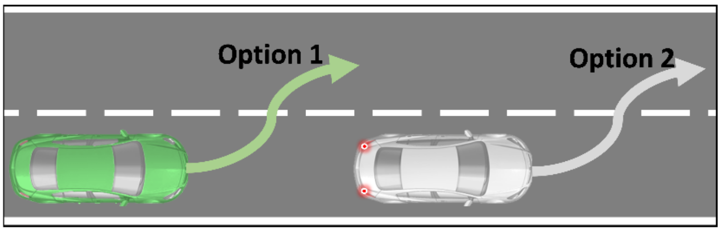

Figure 2-4. Illustration of two possible reasons for activations of unnecessary collision alarms identified in the naturalistic driving studies. Either the ego vehicle (= Option 1) or the lead vehicle (= Option 2) turned or changed lanes. Ego vehicle = green; lead vehicle = grey.

Ten years later, another naturalistic driving study with almost 2000 participants and 200,000 recorded events was conducted over a period of 12 months (Flannagan et al., 2016). Table 2-3 provides an overview of FCA rates and braking response rates of this study compared to the study by General Motors Corporation (2005). The results showed that only 19.4 % of all FCAs were useful correct alarms as they were issued in predefined use cases for preventing rear-end collisions, particularly when approaching a stopped or braking lead vehicle. In response to these alarms, drivers braked in 76 to 81 % of the time. 47 % of all FCAs could be categorized as unnecessary alarms activated in situations in which either the ego or the lead vehicle turned or changed lanes within four seconds after the FCA (see explanation in previous paragraph and Figure 2-4). Drivers responded to these alarms with braking in only 19 % of the time with average decelerations of only 0.4 m/s². The rate of nuisance alarms (2 %) activated by out-of-path events reduced to a large extent in comparison to the previous study by General Motors Corporation (2005). The remaining FCAs were triggered when approaching a slower or accelerating lead vehicle (31 %). These alarms can neither be clearly categorized as hits nor as unnecessary alarms.

Table 2-3

Comparison of FCA Rates and Braking Response Rates between Different Scenarios in the Naturalistic Driving Studies by General Motors Corporation (2005) and Flannagan et al. (2016)

	General Motors Corporation (2005)		**Flannagan et al. (2016)**	
Scenarios	**FCA rate**	**Braking response rate**	**FCA rate**	**Braking response rate**
EV and LV remained in the same lane	27 %	88 %		
LV stopped or decelerated (= Hit)	*No differentiation between these sub-scenarios*		19.4 %	76 – 81 %
LV was slower or accelerated			31 %	46 %
EV or LV left the common lane (=Unnecessary alarm)	32 %	30 %	47 %	19 %
Out-of-path object or vehicle (= Nuisance alarm)	36 %	*n/a*	2 %	34 %
Other	5 %	*n/a*	*n/a*	*n/a*

Note. EV = ego vehicle, LV = lead vehicle.

To sum up, the results of the interview studies and naturalistic driving studies suggested that drivers regularly experience unnecessary alarms when interacting with FCA systems. Data of the naturalistic driving studies revealed that drivers' alarm responses to the same alarm type greatly varied dependent on the context. The following section describes the decision-making process for alarm response execution and provides a categorization of alarm responses.

2.3.3 Decision-making Process for Alarm Response Execution

Dependent on the detection performance of an alarm system, there are different actions an operator can take in response to an absent or present alarm. This section elucidates the decision-making process for alarm response selection and provides an overview about possible alarm responses.

Sorkin and Woods (2009) consider the successful use of an automated alarm system as a combination of the correct detection of both the system and the operator. This approach is referred to as two-stage detection system (Sorkin & Woods, 2009). First, SDT can be used to describe the performance of an alarm system with regard to hazard detection. As a next step, the output of the system serves as input for the operator. Operators' alarm response is based on two cognitive processes: detection and decision (Swets, 2014). As alarm signals in imminent situations are usually designed to be salient enough to attract operators' attention, detection does not play an important role to describe alarm response selection (Bustamante, 2008; Edworthy & Stanton, 1995). In the following, it is always assumed that the operator has successfully detected the alarm.

Decision-making plays an important role in alarm response selection (Bustamante, 2008). Every time the alarm system issues an alarm, the operator has to decide whether and how to respond. Selecting an appropriate alarm response to different types of alarms requires attention management in order to dynamically prioritize and allocate attentional resources to several parallel threads of activity (Woods, 1995). Once an alarm has been successfully detected, the receiver has to combine the alarm with additional information extracted from the environment and with knowledge stored in long-term memory to analyse the nature of the alarm and the underlying alarm trigger (Wogalter, DeJoy, & Laughery, 1999). In consideration of all available information, receivers need to cross-check the validity of the alarm and evaluate the expected value of the outcome of different possible actions (Meyer, 2004; Wiczorek & Manzey, 2011). This cross-check is often difficult and time consuming and is, therefore, associated with effort (Wiczorek & Manzey, 2011). Due to incomplete available information, alarm response selection is usually a decision under uncertainty (Meyer, 2004). In some situations, there are no further available information to cross-check the validity of the alarm. Finally, the receiver selects the action with the highest expected value of a positive outcome and the lowest probability of a negative outcome. The most appropriate alarm response is highly dependent on the classification of an alarm as hit, false alarm, or unnecessary alarm.

	Hazard present		**Hazard absent**	
	Alarm present Hit / Correct alarm	**Alarm absent** Miss	**Alarm present** False alarm	**Alarm absent** Correct rejection
Response present	(1) Necessary response: Correct	(3) Necessary response: Correct	(5) Unnecessary response: Commission error	(7) Unnecessary response: Error
Response absent	(2) Missing response: Error	(4) Missing response: Omission error	(6) No unnecessary response: Correct Omission	(8) No unnecessary response: Correct

Figure 2-5. Categorization of operators' alarm response dependent on the system's previous hazard detection performance.

According to Sorkin and Woods (2009), SDT can also be used to categorize driver reactions in situations with and without an alarm. Figure 2-5 displays the categorization of operators' responses dependent on the system's previous hazard detection performance. According to Meyer (2004), there are two forms of responses to alarm systems: compliance and reliance. The response when drivers act according the alarm signal and take an evasive action is referred to as compliance. Reliance means that operators refrain from performing an action as long as the alarm system does not issue an alarm. Reliance and compliance can cause correct as well as erroneous alarm responses. Under the condition that neither a hazard nor an alarm is present (correct rejection), reliance leads to the correct response to not take any action (Cell 8 in Figure 2-5). However, reliance can also cause so-called omission errors (Cell 4 in Figure 2-5) which denote an absent response to a hazardous event not detected by the alarm system (Mosier & Skitka, 1996). Reliance will not be further addressed in this thesis. Compliance can cause operators to take an evasive action in response to a hit which represents a correct and necessary response (Cell 1 in Figure 2-5). However, taking an evasive action in response to false alarms can be denoted as erroneous unnecessary response (Cell 5 in Figure 2-5). Actions in which operators incorrectly follow activated alarms without verifying it against other available information are defined as commission errors, e.g. when a driver brakes in response to a false collision alarm (Mosier & Skitka, 1996). Instead, the correct response to false alarms would be to ignore the alarm and to refrain from taking evasive actions. This response is referred to as correct omission in this thesis (Cell 6 in Figure 2-5). A lack of compliance can cause an erroneous response when the operator ignores a correct alarm (Cell 2 in Figure 2-5). Not responding to correct alarms in hazardous situations usually has harmful consequences. The phenomenon when people rely too strongly on the detection performance of an alarm system and ignore other information resulting in commission and omission errors is also referred to as complacency (Parasuraman, Molloy, & Singh, 1993), misuse of automation (Parasuraman & Riley, 1997), or automation bias (Mosier, Skitka, Heers, & Burdick, 1998).

Consequently, it does not necessarily reflect safe behaviour to unconditionally take evasive actions in response to an alarm and to not take an action in absence of an alarm. However, it must be considered that a binary categorization of alarm responses as absent or present is a simplified representation of the real world. In the driving context, drivers do not always simply decide to either ignore or to respond to an alarm. Alarm responses can vary from light and short to strong and prolonged braking. With a binary decision, both responses would be equally classified as present response. Therefore, the classification table in Figure 2-5 includes an arrow next to the alarm response cells to illustrate that operator responses to alarms can be better quantified on a continuum than with a binary decision criterion.

With regard to unnecessary alarms, the most desirable alarm response would be a response omission (Cell 6 in Figure 2-5). Analogously to false alarms, evasive actions in response to unnecessary alarms could be interpreted as commission errors (Cell 5 in Figure 2-5). However, it is important to consider that unnecessary alarms are activated by an apparent alarm trigger, such as another vehicle (Lees & Lee, 2007). Therefore, drivers may perform an unnecessary alarm response because the cost of missing a necessary evasive action would be very high. Making a “commission error” in response to unnecessary alarms is not necessarily an erroneous response. It depends on the intensity of the alarm response. An alarm response that constitutes releasing the accelerator pedal or a light braking response would be less hazardous as abrupt and strong braking. Nevertheless, unnecessary alarms may provoke evasive actions which drivers would not have taken without being warned in a certain situation.

The following section provides an overview of empirical research which investigated the impact of false and unnecessary alarms on drivers’ alarm responses.

2.3.4 The Effects of False and Unnecessary Alarms on Driver Behaviour

Previous research showed that operators' compliance with alarms is likely to change over time (for a definition of compliance, see Section 2.3.3). Various studies in the driving context found an effect of frequently issued false alarms on drivers' compliance with correct alarms. Low compliance was manifested through longer reaction times (e.g. Sullivan et al., 2008; Yamada & Kuchar, 2006), decreased reaction rates (Bliss & Acton, 2003), and reduced reaction intensity to correct alarms (Lees & Lee, 2007). This phenomenon is referred to as *cry wolf effect* (Breznitz, 1984). It has been named after the story of "the shepherd who cried wolf" that appears in Aesop's Fables. The fable is about a shepherd boy (= alarm system) who has warned the villagers (= system operators) of the wolf (= hazardous event) that wanted to enter the village to kill their sheep (= harmful consequence) for many times. However, the villagers never saw the wolf because it ran back to its hiding place (= false alarms). At the beginning, the villagers complied with the shepherd's alarms and came unnecessarily to defend their sheep (= commission error; Cell 5 in Figure 2-5). One day, the shepherd cried wolf again but nobody else came to help him in order to defend the sheep (= missing response to correct alarm; Cell 2 in Figure 2-5). On that day the wolf made his move. Operators' compliance with alarms is assumed to change over time due to adaptive learning processes (Meyer, 2001). On the first exposure to an alarm system, operators have initial beliefs and prior knowledge about the system and its reliability. The interaction with low-reliable systems shape their beliefs and knowledge about the system (Meyer, 2001; Sullivan et al., 2008). Dependent on the proportion of alarms that truly require an evasive action due to a present hazardous event (positive predictive value), operators adjust their response criterion *d'* over time by adopting a lower setting (Maltz & Shinar, 2004; Meyer, 2001). Therefore, their compliance decreases and alarm responses become less likely and intense.

The cry wolf effect could be psychologically explained by the experienced contingency between alarm presentation and the need for reaction. In their study, Kiesel and Miller (2007) varied the contingencies between accessory tones and the need for reaction in a reaction time task. Participants were instructed to respond as quickly as possible to a visual stimulus (go trials) and to not respond when no visual stimulus was presented (no-go trials). To vary the contingency of accessory stimulation with response, one group received the accessory tone in 75 % of all go trials and in 25 % of all no-go trials. For the other group, this ratio was reversed. Response times to accessory tones were much faster in the group with a more frequent presentation of accessory tones in go trials than in the group with a more frequent presentation in no-go trials. Therefore, accessory stimuli slowed down reaction times when they usually occurred together with the no-go trials compared to a more frequent combination with go trials. Alarm systems with a low contingency between issued alarms and operators' need to respond to the alarm could similarly slow down response times to correct alarms (= go trials). Accessory stimuli in no-go trials have similarities with false alarms and in go trials with correct alarms.

Studies that examined the effect of unnecessary alarms on compliance with correct alarms provided contradictory results. In a driving simulator study by Cotté, Meyer, and Coughlin (2001), drivers either received unnecessary alarms with objects on the roadside as alarm triggers or false alarms without apparent alarm triggers. Low-reliable alarm systems with a high rate of unnecessary alarms as well as false alarms decreased compliance compared to a high-reliable system with less frequent malfunctions. Moreover, a naturalistic driving study by Sullivan et al. (2008) aimed to investigate if drivers' perceived reliability of prior system performance determines their response time to subsequent alarms. Therefore, responses of 42 drivers to LDWs over a 3-week interval were measured. Alarms could be defined as unnecessary when drivers crossed the lane marking, but no steering response to the alarm was observed with a 6-s time window. Drivers responded faster to LDWs when they had previously experienced a correct alarm rather than an unnecessary alarm. The authors concluded that the perceived reliability of the alarm system has influenced the latency to initiate an alarm response. The results by Sullivan et al. (2008) suggested that, in a naturalistic driving set, the experience of unnecessary LDWs negatively influenced compliance with subsequent alarms in terms of longer alarm response times. In contrast, in two driving simulator studies, compliance with correct alarms was even higher for drivers who experienced a system that regularly issued unnecessary alarms than for drivers who used a perfectly reliable system (Lees & Lee, 2007; Naujoks et al., 2016). Compliance was measured by brake reaction time, brake response frequency, and the magnitude of speed reduction. In both studies, unnecessary alarms were caused by another road user whose behaviour was neither predictable for the system nor for the driver. For example, a vehicle was arriving from the side and finally stopped before it could have taken the participant's right of way. The authors assumed that this finding might be explained by drivers' opportunity to understand the process involved in the activation of an unnecessary alarm, particularly the activation strategy. Their assumption is supported by the results of a study by Gérard and Manzey (2010). Participants were given the opportunity to check the validity of issued alarms with available raw data. Even when interacting with a false alarm prone system, results did not reveal an evidence for the cry wolf effect. Analogously, operators who see and understand the trigger of an unnecessary alarm can cross-check the alarm validity.

Apart from the effects of false and unnecessary alarms on operators' alarm responses to correct alarms, it is important to examine operators' direct responses to these alarm types. Are operators able to ignore false and unnecessary alarms (= correct omission) or do they make commission errors (Figure 2-5)? According to Posner, Nissen, and Klein (1976), urgent alarm signals that include auditory accessory stimuli may cause an increase in commission errors. Rather than considering all available information to cross-check the validity of the given alarm, the arousing effect of auditory accessory stimulus may cause the operator "to respond sooner to the information building up in his memory system" (Posner et al., 1976, p. 161). Additionally, auditory accessory stimuli have been shown to affect response force indicating their influence on motor output processes (Miller, Franz, & Ulrich, 1999). Research on operators' responses to false alarms revealed their general ability to behaviourally discriminate between false and correct alarms. Compared to correct alarms, responses to false alarms are slower (Abe et al., 2002; Maltz & Shinar, 2004), less frequent (Lees & Lee, 2007; Maltz & Shinar, 2007), and less intense (Lees & Lee, 2007). These effects were already present after short-term exposure to the alarm systems. Moreover, it was found that the number of commission errors increased with an increasing number of false alarms. When driving with a system that issued false alarms in 25 % of the time, almost all false alarms (98.3 %) remained without driver reactions (Cummings, Kilgore, Wang, Tijerina, & Kochhar, 2007). The correct omission rate dropped to 60.7 % with a false alarm rate of 75 %. Similarly, Maltz and Shinar (2004) found that an increased number of false alarms resulted in more unnecessary braking responses. In both studies, decision accuracy was negatively related to system reliability. Operators' response criterion β shifted downward with an increasing number of false alarms (see Section 2.3.1). These findings show a tendency towards increased caution and, at the same time, contradict the cry wolf effect.

A driving simulator study by Lees and Lee (2007) revealed short-term effects of unnecessary alarms on alarm responses. The results showed that these alarms caused drivers to brake more often and more intensively than drivers who received false alarms or who did not receive alarms in the same traffic situations. More specifically, drivers responded to unnecessary alarms in 82 % of the time with speed reductions of 12 km/h on average (speed limit of 56 km/h). In a study by Zarife (2014), drivers braked in 66 % of the time in response to a (generic) unnecessary FCA. The study lacks a comparison to driver behaviour in the same situations without unnecessary alarm. In both studies, unnecessary alarms were caused by other road users whose behaviour was neither predictable for the system nor for the driver. For example, a cyclist was approaching the road from the side and finally turned and drove along the sidewalk before it could have crossed the driver's way (Figure 2-6).

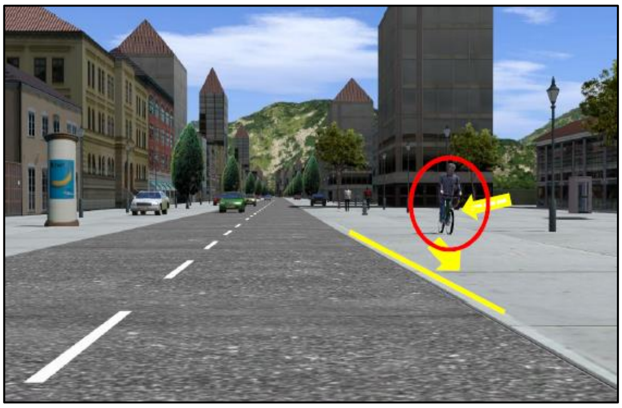

Figure 2-6. Example of an unpredictable unnecessary alarm scenario in the study by Zarife (2014).

Two naturalistic driving studies provided insights into driver responses to unnecessary alarms for long-term system exposure (Flannagan et al., 2016; General Motors Corporation, 2005). In the study by Flannagan et al. (2016), drivers responded with braking in only 19 % of the time with average decelerations of 0.4 m/s². The study by General Motors Corporation (2005) found a braking response rate of 30 % to unnecessary alarms. Importantly, the absence of driver responses did not result in collisions. According to the implemented algorithm, unnecessary alarms were triggered by a stopped or braking lead vehicle (grey vehicle in Figure 2-7). However, the ego and the lead vehicle did not remain in the same lane within four seconds after the FCA. Data suggested that the ego driver (green vehicle in Figure 2-7) either …

1. … intentionally approached the lead vehicle as a prelude to change lanes or to turn (green arrow in Figure 2-7) or
2. … approached the lead vehicle as he or she was able to predict the other's intention to change lanes or to turn out of the lane in the near future (grey arrow in Figure 2-7).

It is assumed that the ego driver could anticipate a dissolving outcome of the inter-vehicle conflict and, thus, did not or only minimally respond to FCAs in these constellations.

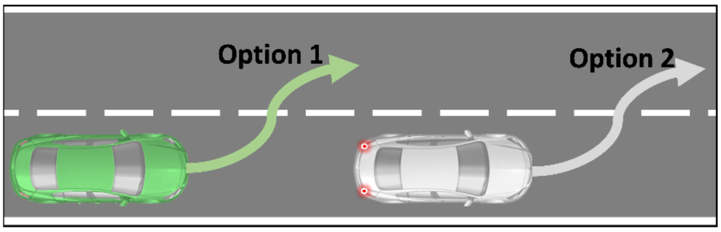

Figure 2-7. Illustration of two possible reasons for activations of unnecessary collision alarms identified in the naturalistic driving studies. Either the ego vehicle (= Option 1) or the lead vehicle (= Option 2) turned or changed lanes. Ego vehicle = green; lead vehicle = grey.

Findings of the cited driving simulator studies and naturalistic driving studies might diverge for two reasons. First, drivers' ability to anticipate a dissolving outcome of a potential inter-vehicle conflict might influence braking responses to unnecessary alarms. In the simulator studies, drivers could not anticipate the behaviour of the other road users (Lees & Lee, 2007; Zarife, 2014). In the field studies, drivers were presumably able to predict their own subsequent actions and those of other road users (Flannagan et al., 2016; General Motors Corporation, 2005). Second, long-term system experience might change the way drivers respond to unnecessary alarms. In the short term, the process of validating an alarm might be more demanding for unnecessary than for false alarms. In contrast to false alarms, there is an apparent alarm trigger for an unnecessary alarm (Lees & Lee, 2007). Therefore, drivers need to additionally comprehend and anticipate if the alarm trigger constitutes a hazard within the next few seconds or not. Prior research showed that the process of validating an alarm requires cognitive resources (Gérard & Manzey, 2010). Without prior experience with situations that usually activate unnecessary alarms, braking responses of moderate intensity might appear to have a lower probability of a negative outcome than not responding to the alarm and taking the risk of a missing response. Such an automated alarm response represents skill-based behaviour (Rasmussen, 1983) and does not require much cognitive resources (see Section 2.1.1). However, as the number of experienced unnecessary alarm situations increases, drivers might develop a schema consisting of traffic constellations that typically activate unnecessary alarms. As a consequence, the process of cross-checking the validity of unnecessary alarms might require less cognitive resources when already expecting a potential alarm activation. Thus, drivers might learn to select a less intense alarm response or to completely ignore the alarm. This assumption is supported by the finding that alarm rates decreased over time in the scenarios where the ego and the lead vehicle did not remain in the same lane after the FCA was issued (Flannagan et al., 2016). The authors argued that drivers were able to anticipate these scenarios and adjusted their behaviour to avoid setting off an alarm.

In conclusion, the research reported in this section showed clear effects of false alarms on drivers' compliance with correct alarms and that drivers are generally able to discriminate their alarm responses to false and correct alarms. However, the impact of unnecessary alarms on driver behaviour remains unclear. Overall, unnecessary alarms seem to have a less negative impact on driver behaviour than false alarms. However, it was shown that unnecessary alarms can result in unnecessary braking reactions under certain circumstances. The following section provides an overview of studies that examined how drivers subjectively perceive and evaluate receiving false and unnecessary alarms.

2.3.5 Subjective Evaluations of False and Unnecessary Alarms

Previous research showed that frequently issued false alarms reduce operators' trust in the system (Abe et al., 2002; Chancey, 2016; Madhavan, Wiegmann, & Lacson, 2006; Naujoks et al., 2016; Wiczorek & Manzey, 2010), system acceptance (Lerner et al., 1996), perceived ease of use, and perceived usefulness (Naujoks et al., 2016). Additionally, operators are annoyed by false alarm prone systems (Lerner et al., 1996; Navarro et al., 2016). Systems with higher reliability are perceived as safer, more pleasing, and agreeable than low-reliable systems (Navarro et al., 2016; Yamada & Kuchar, 2006). These results might be explained by findings of cognitive psychology. Humans are more likely to efficiently process and recall information or experiences that are inconsistent with their initial expectations (schemata) than consistent information (Ruble & Stangor, 1986; Smith & Graesser, 1981). Therefore, errors made by an alarm system might negatively influence operators' subjective evaluations of this system if they initially possessed a schema in which the system works perfectly. However, in a study by Naujoks et al. (2016), false alarms had no impact on participants' intention to use the alarm system.

The impact of unnecessary alarms on drivers' subjective evaluations is less clear than that of false alarms. In a driving simulator study by Naujoks et al. (2016), both unnecessary and false alarms resulted in lower ratings of subjective system reliability compared to a perfectly reliable system. However, in comparison to a perfectly reliable system, unnecessary alarms did not decrease perceived ease of use, usefulness, and trust, while false alarms had a negative impact on these variables. In another driving simulator study, Zarife (2014) found that unnecessary alarms were subjectively rated as very little or little useful. In this study, unnecessary alarms were either generic or combined with information about the alarm object cue. Unnecessary alarms with object cues resulted in higher acceptance ratings than generic unnecessary alarms as the cues might have helped drivers to identify the possibly hazardous object. In line with this finding, Cotté et al. (2001) reported that the ability to see the trigger of unnecessary alarms led older drivers to express greater subjective tolerance for this kind of alarm than for false alarms. Overall, the tendency to perceive unnecessary alarms as less negative than false alarms might be caused by drivers' ability to understand what triggered the alarm in order to verify its validity.

In an interview study by Braitman et al. (2010), 21 % of all respondents indicated that they disliked receiving false or unnecessary alarms. In a naturalistic driving study by Nodine et al. (2011), the rate of annoyance due to unnecessary alarms differed dependent on drivers' age. While 56 % of younger and 42 % of middle-aged drivers who reported to have received unnecessary alarms were annoyed by these alarms, only 17 % of older drivers reported annoyance. Younger drivers were also more likely to report that they received too many unnecessary alarms than older drivers.

The authors of another naturalistic driving study assumed that alarms issued in situations with a dissolving conflict (= unnecessary alarms) were associated with negative ratings of usefulness and acceptance of the FCA system (General Motors Corporation, 2005). As suggestions for improvement, the two ideas most frequently mentioned in a focus group discussion conducted after study participation were to reduce the rate of nuisance and false (= unnecessary) alarms, and to provide the possibility to turn the FCA system off under certain traffic conditions. Another suggestion was that drivers could tell the system which alarms they felt were false or unnecessary. Hence, the system could adapt to their personal driving styles. Flannagan et al. (2016) defined the system deactivation rate (off setting choice) as the primary measure of system acceptance in the field. The results suggested that the number of issued alarms, the alarm modality, and driven miles (odometer) with the LDW system influenced drivers' choice to deactivate the system. The odds ratio of system deactivation increased by 4 percent with every additional alarm on a trip. The LDW system off time was 38 % with haptic seat and 71 %

with auditory alarm. The deactivation rate was lower for the FCA than for the LDW system. The FCA system off time was 6 % with haptic seat and 17 % with auditory alarms.

Farber and Paley (1993) argued that a hit rate of 100 % and a false alarm rate of 0 % is not desirable. When using a perfectly reliable system, drivers would experience the first alarm just before a potential collision. Thus, drivers might not be able to understand the alarm and, hence, would potentially not react fast enough to such an infrequent event. According to Farber and Paley (1993), an ideal detection algorithm might issue alarms in collision-*possible* situations even though drivers would probably be able to avoid the crash. Following this line of thought, not all unnecessary alarms would be harmful. However, an occurrence of the described problem does not seem to become real as alarm systems will probably never reach a reliability of 100 %.

This section demonstrated that unnecessary alarms seem to have a less negative impact on subjective evaluations of alarm systems than false alarms. However, drivers usually recognize receiving unnecessary alarms and prefer a system that is more tailored to their needs. While a large amount of false alarms has already been reduced by technological improvements, there is still a high rate of unnecessary alarms in present-day FCA systems (Flannagan et al., 2016). There is a lack of systematic investigations that compare drivers' acceptance of unnecessary alarms to that of correct alarms and that examine if systems with low perceived reliability influence drivers' overall system acceptance.

In sum, the knowledge built up in Section 2.3 emphasizes the need to investigate the impact of unnecessary alarms on driver performance and acceptance. Moreover, based on the high rate of unnecessary alarms activated by present-day FCA systems, there is a need to improve the perceived system reliability by reducing the rate of unnecessary alarms. As described in the following paragraph, this challenge can be addressed by adaptive assistance systems.

2.4 Adaptive Assistance Systems

The previous section has described the problems that arise with low-reliable alarm systems or rather systems with low *perceived* reliability. Most of ADAS' present-day alarm activation algorithms do not sufficiently consider whether the driver currently actually needs assistance. In order to increase the perceived system reliability by reducing the rate of unnecessary alarms, systems need to tailor alarm activation to drivers' needs (Petersson, Fletcher, Barnes, & Zelinsky, 2004).

Adaptive assistance systems adjust system behaviour to consider drivers' changing need for assistance when performing complex tasks in dynamic environments (Feigh, Dorneich, & Hayes, 2012). These systems are often compared to a skilled human co-driver who warns the driver only if necessary to avoid information overload and annoyance (Feigh et al., 2012; Inagaki, 2008; Petersson et al., 2004). This comparison assumes that the human co-driver has an overall understanding of the traffic situation. This includes the comprehension of an evolving critical situation outside the vehicle and observing the driver's current state, awareness, intentions, and reactions inside the vehicle. An unobtrusive co-driver would only warn the driver when expecting a missing, delayed, or inappropriate driver reaction.

For the implementation of adaptive systems, it must be defined how, when, and to which parameters the system behaviour should be adapted. Section 2.4.1 provides an overview of different adaption strategies that specify when and how to adapt system behaviour. Section 2.4.2 takes a closer look at different adaption parameters that can determine system behaviour.

2.4.1 Adaption Strategies

"The ideal goal is to give the drivers the information they need, at the right moment, in the right situation and in the right way" (Simon, 2005, p. 40). This quote already provides indications of different adaption strategies. The points "the information they need" and "in the right situation" can be assigned to negative adaption strategies, "at the right moment" to positive adaption strategies, and "in the right way" to neutral adaption strategies. The following paragraphs and Table 2-4 provide an overview of adaption strategies using visual attention as exemplary adaption parameter.

A *negative* adaption strategy aims to reduce the rate of unnecessary alarms by suppressing alarms that are deemed unnecessary (Smith, Witt, Bakowski, LeBlanc, & Lee, 2008, p. 510). Alarm suppression is associated with drivers' currently low need for assistance, e.g. when their visual attention is directed towards the road. It is assumed that the strategy of suppressing alarms during periods of low need for assistance is unlikely to reduce safety (Smith et al., 2008). Studies that applied this strategy by suppressing LDWs and FCAs when drivers were visually attentive have found a significant reduction of alarm rates (Hammoud et al., 2008;

Trefflich, 2010). In the study by Hammoud et al. (2008), drivers rated the adaptive FCA and LDW systems as more useful than the non-adaptive system and indicated a preference for the adaptive systems. The most common reason for this preference was the lower alarm rate.

Table 2-4

Adaption Strategies Related to Visual Attention as Adaption Parameter

	Adaption parameter (visual attention)	
Adaption Strategy	Low need for assistance (eyes on the road)	High need for assistance (eyes off the road)
Negative	No Alarm	Baseline alarm
Positive	Baseline alarm	Earlier alarm
Neutral	Less urgent alarm	Baseline alarm

Note. Baseline alarm represents the alarm as it would be activated by a non-adaptive system.

A *positive* adaption strategy adapts the alarm timing to an adaption parameter, such as drivers' current level of visual attention towards the road (Smith et al., 2008). When drivers' need for assistance is assumed to be low, the original alarm activation threshold remains at a constant level. Alarms are activated earlier during periods where need for assistance is assumed to be high, e.g. when the driver is visually distracted. The goal of this strategy is to improve the safety strategy of assistance systems (Smith et al., 2008). However, this strategy inevitably increases the total number of alarms. Additionally, the earlier alarms are activated, the more likely they are interpreted as unnecessary (Brouwer & Hoedemaeker, 2005). Studies that used this adaption strategy to provide earlier collision alarms for visually distracted drivers showed that drivers accepted these alarm systems less or as much as non-adaptive alarm systems (Brouwer & Hoedemaeker, 2005; Brown, Marshall, Moeckli, & Smyser, 2007). These findings suggested that positive adaption strategies are not applicable to improve the perceived reliability of an assistance system. Therefore, this strategy is not further considered in this thesis.

A third category of adaption strategies is referred to as *neutral* adaption strategy in this thesis. In contrast to negative and positive adaption strategies, a neutral adaption strategy does not influence the total number of alarms as it only adapts the alarm design in order to provide information on the alarm significance and meaning. The roots of this adaption strategy lie in the concept of likelihood alarm systems (LAS) that were originally studied in complex human-machine systems in which the operator has the role of a supervisory control (Sorkin, Kantowitz, & Kantowitz, 1988). These systems do not only alert the operator to a possible critical event but compute the likelihood of its occurrence. The likelihood of a critical situation and, thus, also the urgency of an alarm response is encoded into varying levels of alarm signals on three or more stages, e.g. by using different word messages (Sorkin et al., 1988; Wickens & Colcombe, 2007), loudness or pitch of auditory alarms (Lee, Hoffman, & Hayes, 2004), intensity and frequency of haptic alarms (Ho & Sarter, 2016; Lee et al., 2004), colours of visual alarms (Petersson et al., 2004; Sorkin et al., 1988; Wickens & Colcombe, 2007; Wiczorek & Manzey, 2011), or combinations (Bustamante, 2008). Research showed that LAS improved operators' decision-making accuracy and increased the number of correct alarm responses compared to a conventional binary alarm system (Bustamante, 2008; Wiczorek & Manzey, 2011). These results might be explained by a supportive effect of the LAS on operators' attention management in terms of efficient allocation of information-processing resources (Sorkin et al., 1988). By providing information about the urgency of alarm responses, alarms of LAS are supposed to support users' preattentive evaluation of the alarm and, thereby, reduce undesired alarm responses (Sarter, 2005; Woods, 1995). While low-priority alarms do not require an immediate shift of attention away from the primary task, high-priority alarms intend to automatically shift operators' attention to the critical event. Operators can attend and respond to a low-priority alarm after some delay or completely ignore it, while they need to immediately respond to high-priority alarms.

Lee et al. (2004) compared graded collision alarms with three levels to binary alarms. Participants experienced either visual-auditory alarms with varying levels of loudness or visual-haptic alarms with negligible, moderate, and severe intensity and frequency. Graded collision alarms provided greater safety margins and induced fewer inappropriate braking responses than binary alarms. Differences in subjective ratings were not only dependent on the alarm strategy but also on modality. Drivers indicated higher trust in graded haptic alarms than in graded auditory and single-stage auditory alarms. Binary auditory alarms were rated as more annoying than binary and graded haptic alarms. Maltz and Shinar (2007) compared auditory collision alarms with graded intensity dependent on the headway to the lead vehicle with binary alarms on different levels of system reliability. In the high-reliable condition, no participant perceived the binary alarm system as annoying, while the graded alarms were perceived as annoying by 30 % of the participants. This result may be related to the fact that participants received a higher number of alarms with the graded than with the binary alarm system in this condition. Additionally, the binary alarm system exclusively issued correct alarms. In the low-reliable condition, the rate of annoyed participants increased to 30 % with binary alarms, and the rate of annoyed participants with graded alarms decreased to 20 %. A possible explanation could be that the binary alarm system activated more false alarms in the low-reliability condition while the alarms with graded intensity contained information about the alarm reliability.

So-called differential display modalities represent another realization of neutral adaption strategies (Smith et al., 2008). This strategy provides different types of alarms for the same critical event in the environment depending on the drivers’ assumed need for assistance. For example, the system activates a visual-only collision alarm when the driver’s visual attention is directed to the forward scene and a visual-auditory alarm when the attention is directed elsewhere. A study by Naujoks et al. (2016) found that visual-only false alarms did not have a negative impact on drivers’ compliance. A possible explanation for this finding might have been that visual-only alarms suppressed the auditory component that many drivers perceive as intrusive and, therefore, they perceived false alarms as more “pardonable” (Naujoks et al., 2016; Smith et al., 2008). This finding supports the use of differential display modalities. In contrast to alarm suppression, visual-only alarms during periods of low need for assistance could help drivers to understand the underlying functionality of an adaptive alarm system (Smith et al., 2008). Section 2.4.3 will take a closer look on the influence of adaptive assistance strategies on the development of operators’ mental models.

To make use of the described adaption strategies, an adaptive system must be aware of drivers’ current need for assistance. To decide when to adapt system behaviour, the system must define and measure adaption parameters (Feigh et al., 2012). The following section provides an overview of potential adaption parameters in the context of ADAS, their implementation in prior research, and their effects on driving performance and drivers’ subjective evaluations.

2.4.2 Adaption Parameters

Adaption parameters are assumed to be associated with drivers’ need for assistance. The system must integrate information about the environment, the vehicle, *and* the driver to enable intelligent adaption to driver needs (Cheng & Trivedi, 2006; Doshi & Trivedi, 2008). The current need for assistance may change dependent on situational demands, drivers’ current state, and their intention (Feigh et al., 2012). The following sections address these adaption parameters.

2.4.2.1 Situational Demands

Situational demands represent a possible adaption parameter (Kassner, 2011). Prior research has already adapted driver assistance to different levels of situational demands while keeping the critical event at a constant level. For example, Hjälmdahl and Thorslund (2006) adapted the timing of FCAs to the friction of the road. Alarms were activated earlier when driving on a slippery road than on a dry road (positive adaption strategy). A comparison between the adaptive and a non-adaptive FCA system revealed safety benefits of the adaptive system in terms of longer minimum headways and higher time to collision values resulting in fewer collisions on slippery roads. There was no difference in drivers' acceptance ratings between the non-adaptive and adaptive system.

2.4.2.2 Driver State

In research literature, there is a consensus on the impact of the driver state or operator functional state on the need for assistance (Hajek, Gaponova, Fleischer, & Krems, 2013; Schaap, 2012; Schwarz & Fuchs, 2014; Wilson & Russell, 2003). As described in Section 2.1.3, the driver state is associated with visual attention and mental workload. The driver state influences situation awareness on different levels and, thus, determines the driver's ability to carry out the driving task at a certain moment in time. Consequently, drivers' experience of the objectively measured criticality of a situation and their current need for assistance might be dependent on their current focus of visual attention and if there are enough available cognitive resources to appropriately comprehend the situation and to anticipate the future status.

Visual attention represents the adaption parameter most frequently used and investigated in prior research (Blaschke, Breyer, Färber, Freyer, & Limbacher, 2009; Hammoud et al., 2008; Pohl, Birk, & Westervall, 2007; Tijerina et al., 2010; Trefflich, 2010). Hammoud et al. (2008) argued that visually attentive drivers are more likely to perceive assistance as annoying and unnecessary than inattentive drivers. FCA and LDW systems that suppressed alarms when drivers were visually attentive were rated as more useful and preferable than a non-adaptive system (Hammoud et al., 2008). However, alarm suppression dependent on visual attention does not necessarily always match the driver's current need for assistance. There is a potential risk to increase the number of missed alarms. Results of a naturalistic driving study showed that drivers' visual attention was directed towards the road in 40 % of all recorded incidents, near-crashes, and crashes (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Consequently, directing visual attention to the forward scene does not necessarily result in an adequate comprehension, anticipation, and consequently decision and action execution. To determine whether the driver is aware of the situation to which his visual attention is directed, his or her cognitive workload must be additionally taken into account.

Mental workload could serve as alternative or additional adaption parameter. According to Wickens' multiple resource theory, two or more tasks performed simultaneously increase the level of mental workload (Wickens, 1984). Thus, drivers have less cognitive resources available to comprehend the current traffic situation and to predict future events (see Section 2.1.3). High mental workload has a detrimental impact on drivers' situation awareness and driving performance (Horrey & Wickens, 2004; Kass, Cole, & Stanny, 2007). As far as known, there was only one study that adapted driver assistance to mental workload (Reinmueller et al., 2018). Mental workload was manipulated by conversation engagement. Using a neutral adaption strategy, drivers received high support with vibrotactile-auditory FCAs while being engaged in a co-driver conversation and received low support with auditory-only FCAs without conversation. Independent of the current level of mental workload, drivers responded faster to high-support than to low-support alarms.

2.4.2.3 Intention

Driver intention represents another promising adaption parameter (e.g. Inagaki, 2008; Lethaus & Rataj, 2007; Streubel & Hoffmann, 2014). In human-human interaction, theory of mind describes the human ability to comprehend intentions (and other mental states) of other persons by relating observable actions to underlying mental states (see Section 2.1.2.4) (Meltzoff, 1995; Premack & Woodruff, 1978). With regard to human-machine interaction, a system capable of predicting the driver's intended future actions, manoeuvres, and trajectories offers several possibilities to adapt assistance to the needs of the driver. First, based on the driver's detected planned trajectory, a system would be able to identify dangerous situations, such as a potential collision at an intersection, and choose an appropriate way to assist the driver (Streubel & Hoffmann, 2014). Associated therewith, an FCA system would activate alarms only if the potential obstacle lay in the driver's planned trajectory. Second, the prediction of drivers' manoeuvre intentions may help to provide assistance only during situations that evolved unintentionally. For example, an LDW system would activate an alarm only if the driver was about to leave the lane unintentionally. However, the system could suppress the alarm as soon as it detects an intentional lane change. Third, if the system inferred a delay in a required evasive action (e.g. braking), it would be able to adapt the level or timing of assistance (Inagaki, 2008; McCall & Trivedi, 2009). In turn, the system could suppress alarms when the driver is already in the process of reacting, e.g. braking (Stevens, 2012). The relevance of such an adaption is demonstrated by the finding that drivers' trust in subsequent alarms decreased when they received alarms in situations in which they had already decided to brake (Abe & Richardson, 2006).

For a successful implementation of adaptive assistance systems, there remain at least three challenges which are addressed in the following section.

2.4.3 Challenges of Adaptive Systems

First and most importantly for this thesis, very little is currently known about adaption parameters that appropriately represent drivers' actual need for assistance. Despite intensive research, the measurement of the corresponding adaption parameters still remains the second challenge of adaptive systems. Third, drivers might have problems to develop an adequate mental model of adaptive systems. The following paragraphs describe each challenge in more detail.

Overall, previous research provided insights into adaption parameters that might be relevant to represent drivers' need for assistance. However, prior work based the selection of adaption parameters basically on hypotheses, e.g. "Conversations were assumed to increase driver workload, and thus increase the need for support." (Reinmueller et al., 2018, p. 244), "...alerts are only useful for drivers who are not visually attending to the forward roadway" (Smith et al., 2008, p. 505), and "human intent is a critical piece of information for determining whether the system's actions will help or hinder the user" (Cheng & Trivedi, 2006, p. 28). Little attention has been paid to the impact of different adaption parameters on driving performance and on drivers' subjective system evaluations. Do drivers really not want to receive a collision alarm when they are looking towards the road? Does it represent the drivers' wish to receive a different type of alarm when being involved in a passenger conversation? For example, participants who took part in an on-road study by LeBlanc et al. (2006a) expressed concerns about the suppression of alarms when their eyes are on the road while being tired or cognitively distracted. These concerns are underlined by the finding that drivers were looking on the road in 40 % of all recorded incidents, near-crashes, and crashes (Klauer et al., 2006).

Furthermore, adaptive systems must be able to reliably measure the corresponding adaption parameters. This includes the challenge of the identification of valid indicators. Additionally, series vehicles are usually not equipped with the necessary measurement instruments. For example, driver monitoring systems need to use 2D and 3D cameras for eye or head tracking, speaking detection, and hand position determination (Pech, Enhuber, Wandtner, Schmidt, & Wanielik, 2019). Visual attention can be measured by eye gaze and head pose tracking systems (e.g. Petersson et al., 2004; Pohl et al., 2007; Tijerina et al., 2010) or derived from drivers' use of in-vehicle information systems (Blaschke et al., 2009). In comparison to the measurement of visual attention, it is more difficult to assess if drivers are aware of the situation to which their visual attention is directed to (Inagaki, 2008). According to prior research, the current level of cognitive workload can be estimated from situational demands (Smith & Zhang, 2004), measured with physiological data, such as eye movement activity, heart rate variability, or electrodermal activity (Ahlstrom & Friedman-Berg, 2006; de Waard, 1996; Liang, Lee, & Reyes, 2007; Schwalm, 2009), or inferred from driving performance (Liang et al., 2007). With regard to intention detection, the aim is not only to recognize an action before it is fully disclosed as an online-assessment of the initial part of the action (*early activity recognition*), but also to forecast what the human intends to do prior to real time (*intention prediction*) (Doshi & Trivedi, 2011; Rouse, 1988; Zunino et al., 2017). To detect a manoeuvre, early activity recognition uses the change in the vehicle's motion in response to the driver's input when the manoeuvre has already begun (Lethaus & Rataj, 2007). Driving manoeuvres like intersection turns and lane changes are defined by a specific series of operations including pedal presses and steering adjustments (Doshi & Trivedi, 2011). By analysing the events or movements which are specific of the subsequent manoeuvre, drivers' manoeuvre intentions could be predicted prior to the actual start of the manoeuvre (Doshi & Trivedi, 2011; Zunino et al., 2017). Previous research has identified drivers' eye gaze, head dynamics, hand position, body pose, foot hovering information, and context information as relevant cues to predict driver intentions (e.g. Cheng & Trivedi, 2006; Doshi & Trivedi, 2009; McCall & Trivedi, 2009; Rodemerk, Winner, & Kastner, 2015; Smith & Zhang, 2004).

Adaptive systems might face a challenging trade-off (Smith et al., 2008). On the one hand, without being adapted to users' needs, systems are likely to activate many alarms that users perceive as unnecessary. On the other hand, adaptive alarm activation strategies could interfere with the development of a correct mental model of the alarm system. Mental models represent the user’s cognitive representation of how a system operates. They enable an individual to understand, predict, and describe system behaviour (Rouse & Morris, 1986). The mapping between events in the environment and alarm occurrence is more complex for adaptive systems than for non-adaptive systems. Therefore, drivers could perceive system behaviour as inconsistent as similar external events sometimes trigger an alarm and sometimes not (Smith et al., 2008). They might erroneously conclude that the system did not accurately detect the external critical event. Trefflich (2010) found that drivers rated a non-adaptive system as more predictable than an adaptive system. As a consequence, system trust, acceptance, and perceived safety may decline which would cancel out the potential benefit of adaptive systems (Smith et al., 2008). It is assumed that an adequate mental model is a crucial factor for both acceptance and success of adaptive systems. The underlying functionality of an alarm system with neutral adaption strategy might be more transparent to the driver than that of a negative strategy (Smith et al., 2008). Instead of suppressing certain alarms, these systems only vary a certain aspect of the alarm.

Section 2.4 focused on adaptive systems that aim to tailor assistance to user needs to overcome problems caused by low-reliable assistance systems prone to unnecessary and false alarms. In addition to different strategies that can be implemented in adaptive systems, the section provided an overview of potential adaption parameters. Taken together the most important points for this thesis, very little is currently known about factors that effectively influence drivers’ need for assistance and if the proposed adaption parameters (see Section 2.4.2) adequately reflect user needs. A systematic understanding of drivers’ need for assistance is still lacking. To be able to appropriately adapt driver assistance to drivers’ needs, it is necessary to identify factors that determine drivers’ need for assistance. In which situations do drivers benefit from alarms and perceive alarms as useful? In contrast, in which situations do alarms not improve or even impair driver performance and are perceived as unnecessary? The next section provides insights into a factor that could be associated with drivers’ need for assistance.

2.5 Subjective Hazard Perception and Drivers' Need for Assistance

To achieve a broad understanding of factors that potentially influence drivers' need for assistance, a literature analysis that considered quantitative as well as qualitative research results was conducted. The cited results are related to the human's *perceived* or rather *self-reported* need for assistance based on subjective evaluations, surveys, comments, and interviews. Based on the analysis, drivers' retrospective subjective hazard perception of the encountered traffic situation has been identified as a potential determinant for drivers' perceived need for assistance. Research in the area of static product warnings showed that perceived hazardousness of a product positively influenced warning effectiveness, perceived necessity of warnings, and compliance with warnings (Laughery & Wogalter, 2006; Wogalter, Brelsford, Desaulniers, & Laughery, 1991). With reference to driver assistance, a user needs web-based survey with 1049 participants showed that drivers state to have a greater need for driver assistance in critical situations (van Driel & van Arem, 2005). In an interview study, 37 % of the respondents reported that they did not need those FCAs that were triggered when they themselves did not perceive a crash risk (Eichelberger & McCartt, 2014). Furthermore, in two naturalistic driving studies with vehicles equipped with LDW and FCA systems, driver comments suggested that low compliance with alarms and low ratings for alarm usefulness were associated with a mismatch between alarm activation and drivers' subjective hazard perception (LeBlanc et al., 2006b; Portouli et al., 2006). More specifically, many participants rated alarms as (rather) useless on the ground of no perceived danger in the situation, e.g. "It doesn't look like any danger existed" (LeBlanc et al., 2006b, p. 372).

With regard to human subjective hazard perception, drivers' online situational risk awareness within an encountered situation (Gauss, 2008) and their subjective hazard perception concerning the overall traffic situation in retrospect must be differentiated. Situational risk awareness that drivers carry out continuously during driving can be considered as a component of situation awareness (Gauss, 2008). More specifically, it is part of the comprehension and anticipation stage and represents the driver's awareness of the risk associated with the current situation. For example, the driver's awareness of the situational risk can be influenced by situational demands (e.g. road friction, visibility conditions) or the current driver state (e.g. drowsiness, visual attention). To avoid an undesired outcome of the situation, a high situational risk awareness would lead the driver to execute an evasive action. However, the perception, comprehension, and anticipation of elements of the current situation are error-prone (see Section 2.1.3) and, thus, drivers might not always be aware of the real situational risk. For example, a driver might not be able to comprehend and to anticipate that a crash is about to occur while episodes of visual distraction. In this moment, the driver's risk awareness would be inadequately too low. However, it is assumed that the driver derives a higher subjective hazard perception concerning the overall traffic situation in retrospect. This evaluation refers to a completed scenario. The retrospective subjective hazard perception is expected to be higher as the situational risk awareness as soon as the driver has noticed that he or she missed important information that might have almost or actually caused a collision. In such situations, drivers are assumed to perceive activated alarms as supportive and useful. With regard to the relationship between drivers' subjective hazard perception and need for assistance, this thesis specifically considers drivers' *retrospective* subjective hazard perception of a traffic situation as the essential factor that predicts drivers' need for assistance.

To sum up, the presented research proposes two assumptions about factors that influence drivers' perceived need for assistance. First, subjective hazard perception and need for assistance seem to be positively related to each other. The higher the drivers' retrospective subjective hazard perception of the overall encountered traffic situation, the higher the currently perceived need for assistance. Second, the presented research suggests that the system's risk assessment does not always match the level of human subjective hazard perception. Such a discrepancy conceivably renders alarms less useful or rather unnecessary in the eyes of the drivers, particularly when the system risk assessment is higher than drivers' subjective hazard perception. This assumption can be explained as follows. A high system risk assessment of the current situation results in alarm activation. At the same time, a low subjective hazard perception is assumed to lead to a low need for assistance. Consequently, the system would provide assistance while the driver has a low need for assistance. In contrast, it is assumed that a match between high system risk assessment and high human subjective hazard perception results in alarms that drivers perceive to be useful. In turn, when both system risk assessment and subjective hazard perception are low, the system would not trigger an alarm while the driver has a low need for assistance (correct rejection). The knowledge built up in this section and the derived assumptions were considered for the development of a theoretical framework of drivers' subjective alarm evaluation. This framework is explained in the following chapter.

3 Development of Research Questions

Drivers who use present-day FCA systems regularly experience unnecessary alarms (see Section 2.3.2). Prior research revealed that unnecessary alarms seem to have a less negative impact on driver performance and subjective evaluations than false alarms. However, unnecessary alarms can cause superfluous braking reactions (see Section 2.3.4). Additionally, drivers recognize receiving unnecessary alarms and they report to prefer an alarm system that tailors alarm activation more to their current need for assistance (see Section 2.3.5). It remains unclear which factors influence drivers' responses to and subjective evaluations of unnecessary alarms. In summary, there have been no controlled studies that examined the impact of unnecessary alarms on driver performance and acceptance. Moreover, even though there has been much research on adaptive assistance systems, there is still very little scientific understanding of which factors determine drivers' need for assistance (see Section 2.4). No previous study systematically investigated why drivers perceive certain alarms as unnecessary. Thus, there is need for research in this area.

To develop a systematic understanding of drivers' need for assistance, the overarching objective of this thesis was to contribute knowledge about psychological factors and processes that influence drivers' perceived need for assistance in potential collision situations. Accordingly, the empirical research aimed to identify specific traffic constellations that result in alarm activations that drivers perceive to be unnecessary. In addition, this thesis sought to examine the impact of unnecessary alarms on drivers' responses and acceptance.

3.1 Theoretical Framework of Drivers' Subjective Alarm Evaluation

This chapter introduces a theoretical framework that served as a basis to derive specific hypotheses about psychological factors and processes that might determine drivers' need for assistance (Figure 3-1). Related thereto, the framework sought to elucidate under which conditions drivers evaluate alarms as unnecessary or useful. The research presented in this thesis investigated the hypotheses derived from the framework.

Figure 3-1 illustrates that the framework consists of two parts representing the processes that conclude in the system's alarm decision (on the left side) and in the driver's perceived need for assistance (on the right side). The graphical arrangement of the two processes in the model demonstrates that the major stages of system and human situation awareness and subsequent situation evaluations are assumed to be comparable (Schmidt, 2012). The framework serves to describe, compare, and contrast the stages of these two processes. On the basis of identified relationships, discrepancies, and commonalities, hypotheses concerning the research questions are derived. Detailed descriptions of the system's alarm activation process can be found in Section 2.2.2 and of drivers' situation awareness and involved cognitive processes in Section 2.1.2.

While the system perceives environmental objects and their behaviour with sensors, human drivers use their senses to perceive relevant elements in the environment. The system's situation analysis represents human comprehension and the system's prediction level is comparable to human anticipation. Based on the levels of situation awareness, the system assesses a certain level of risk and the human driver develops a retrospective subjective hazard perception. On the last stage, the system derives its alarm decision while the human driver derives a certain level of need for assistance. Resuming the content of Section 2.5, the theoretical framework proposes the following hypothesis.

> **Hypothesis I.** Drivers' retrospective subjective hazard perception predicts their perceived need for assistance.

The hypothesised relationship represents the last two stages of the human process in the theoretical framework and is illustrated on the lower right part of Figure 3-1. There are two feedback loops in the theoretical framework. First, alarms become a part of the environment perceived by the driver. Second, an action that the driver executes is also sensed and analysed by the system.

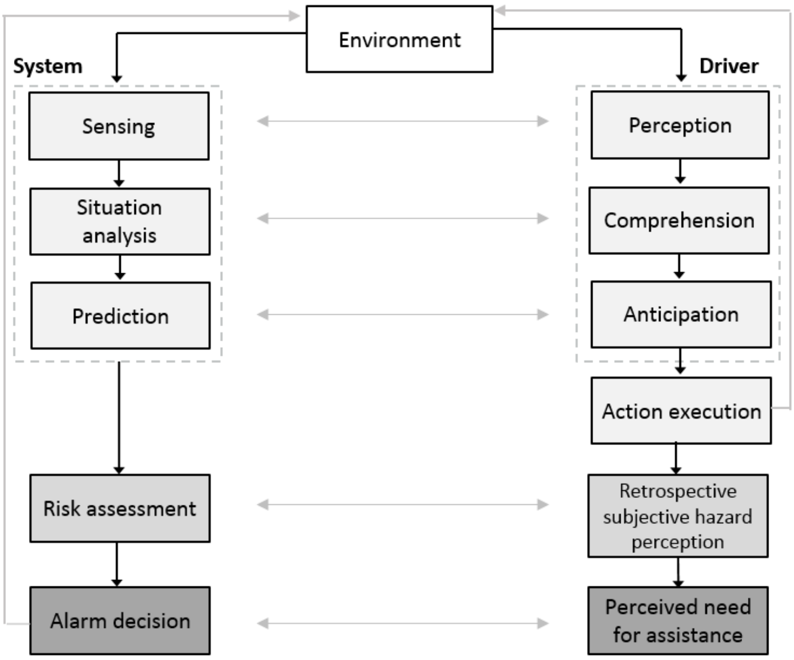

Figure 3-1. Theoretical framework of drivers' subjective alarm evaluation.

The research results reported in Section 2.2.3 provide insights into the conditions under which alarms seem to be *useful*, measured by their positive effect on driving performance. These assumptions are shown in the left panel of Figure 3-2. According to the theoretical framework of drivers' subjective alarm evaluation, useful alarms are associated with a match between alarm activation and drivers' increased perceived need for assistance. This match, in turn, is assumed to be based on a previous match between system risk assessment and human subjective hazard perception. This consistency is caused by an event that requires immediate action while the alarm system has advantages over drivers' situation awareness on at least one of the three levels *or* the system and the driver were equally aware of the situation. With regard to the anticipation level, prior research suggested that the alarm system needs to have advantages over the driver to improve driving performance (Schmidt, 2012; Stahl et al., 2016).

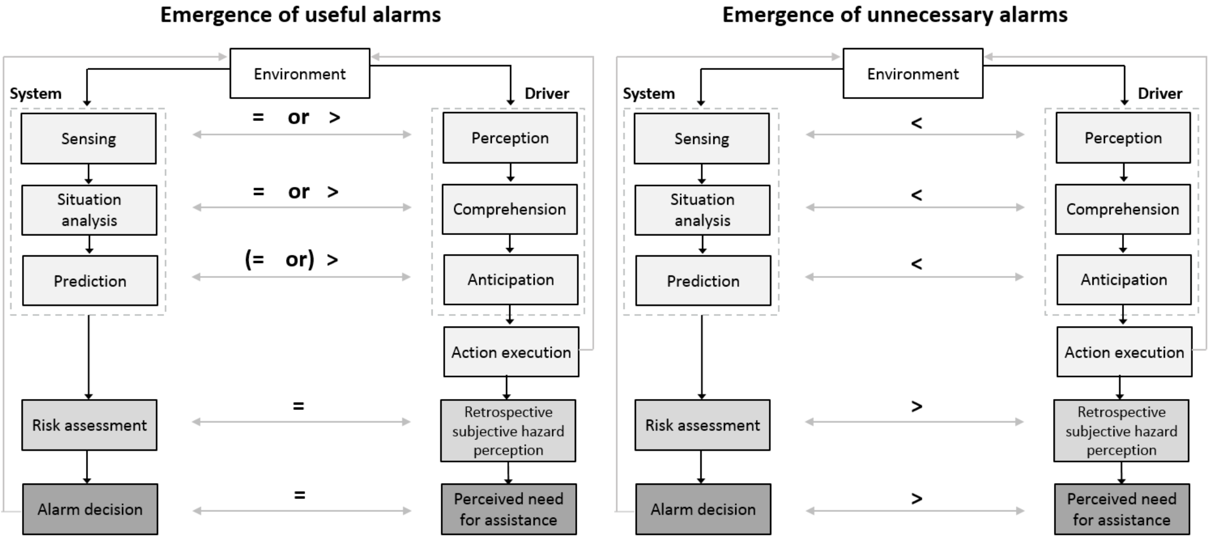

Figure 3-2. Hypothesised prerequisites for the emergence of useful alarms (left) and unnecessary alarms (right) in the theoretical framework of drivers' subjective alarm evaluation.

As described in Section 2.5, drivers might perceive alarms as unnecessary when there is a discrepancy between system risk assessment and drivers' subjective hazard perception (lower right part of Figure 3-2). Thus, a further hypothesis is derived.

> **Hypothesis II.** A situation which simultaneously leads to a high system risk assessment and a low subjective hazard perception renders alarms that drivers perceive as unnecessary.

There is a need to examine how such a discrepancy arises. The following paragraphs contain theoretical considerations on factors that might potentially result in the fact that the same traffic situation is evaluated as more critical by the alarm system than by the driver.

System risk assessment is usually based on the kinematics of the current driving situation. Environmental events with identical physical measurements consistently result in an identical level of system risk assessment whenever the corresponding values fall below a predefined threshold. The progression and outcome of a potential conflict with another road user is not considered by the system. The system's rule-based and logical alarm activation strategy represents an appropriate concept for simple and clear situations in which the potential conflict with another road user remains. However, it might have shortcomings in more complex situations where a potential conflict dissolves in the further course. To develop their situation awareness, human drivers are supposed to take into account additional factors which are concurrently not considered by the system. The following subsections address possible reasons for advantages of the human driver over the system on each level of situation awareness. All considerations presuppose a visually and cognitively attentive driver.

3.1.1 Human Perception and System Sensing

Human perception might have advantages over system sensing. The driver is be able to visually perceive what is happening outside the vehicle's sensor area that could be relevant to develop a holistic comprehension and to correctly anticipate the further course of the situation, e.g. other vehicles or vulnerable road users in front of the lead vehicle, at the roadside, or in side streets.

3.1.2 Human Comprehension and System Situation Analysis

Human comprehension can have advantages over the system's situation analysis. For example, an FCA system would be able to sense lane markings with its camera. However, on the level of situation analysis, not every present-day FCA system takes this knowledge into account. In a sharp curve with a slower vehicle ahead in the adjacent lane that is driving in the same direction, the TTC value can fall below the critical threshold (Figure 3-3). The driver would comprehend that the potential conflict with the other vehicle dissolves as it is driving in a different lane. In contrast, the system would not consider the lane markings for its situation analysis. Consequently, the system's risk assessment is high while the driver would perceive the situation as non-hazardous.

Figure 3-3. A driving situation from a driver perspective (left) and a bird's-eye view (right) in which drivers comprehend that the alleged lead vehicle does not constitute a crash risk.

Based on schemata stored in long-term memory, drivers can integrate multiple and complex elements into a holistic comprehension of the situation. By adopting prior experiences to new situations, they are able to identify stereotypical traffic situations (Stahl et al., 2014). A combination of specific cues in the environment can result in the recognition of a stereotypical situation in which the lead vehicle typically does not longer remain in the same lane. This knowledge is not available to the alarm system. On the situation analysis level, the system's representation of the situation is simply based on the current status of other road users located in its sensor area merged with the current status of the ego vehicle. Thus, the system has difficulties to analyse the meaning of multiple and complex environmental cues to achieve a complete understanding of the situation. The human comprehension of environmental cues constitutes a basis for the anticipation of the lead vehicle's behaviour within the next few seconds.

3.1.3 Human Anticipation and System Prediction

On the prediction level, FCA systems mainly use the TTC criterion to predict the position of the ego vehicle in relation to other objects. However, these measurements only make valid predictions under the condition that both the ego and the other road user *remain on the same path* at constant speed. However, traffic constellations with identical TTC values can result in different outcomes. While the system is not able to predict the further course of the situation, it is assumed that drivers are usually able to anticipate whether potential inter-vehicle conflicts remain or dissolve in the near future. To anticipate if another road user will still constitute a crash threat in the course of time, drivers might additionally consider their own manoeuvre intention and those attributed to other road users (see Section 2.1.2.4).

First, drivers' anticipation might have advantages over the system's prediction as they are supposed to consider their own manoeuvre intention for anticipation. The identification of the same stimulus in the environment can trigger different actions dependent on drivers' current manoeuvre intention (Cohen & Huston, 1994). Based on prior experiences, drivers have learned which action effects are usually attained by a certain intentional action (e.g. Herbart, 1825). A standing or braking lead vehicle ahead can either trigger a strong braking response when the driver intends to stay in the lane or a steering response without or only a slight braking response when the driver intends to change lanes or to turn. These theoretical considerations are supported by data of the naturalistic driving studies by General Motors Corporation (2005) and Flannagan et al. (2016). In these studies, a high amount of unnecessary FCAs was issued in situations in which the ego driver changed lanes or turned after alarm activation. This scenario is illustrated by the first option in Figure 2-7. In these situations, TTC values presumably fell below alarm activation thresholds because ego drivers tailgated as a prelude to pass the lead vehicle, change lanes, or to turn. Drivers' current intentions conceivably led to an anticipation of a dissolving conflict and, thus, to the corresponding action selection (no or minimal alarm response).

A further advantage of the driver on the anticipation level could be the ability to anticipate subsequent actions of other road users based on the prior identification of stereotypical traffic situations. It is assumed that drivers can infer intentions of other road users from specific cues in the environment (Ansuini et al., 2015; Zunino et al., 2017). In the naturalistic driving studies by General Motors Corporation (2005) and Flannagan et al. (2016), unnecessary alarms were also associated with situations in which the lead vehicle left the common lane shortly after alarm activation. According to the assumptions of this thesis, ego drivers were conceivably able to anticipate the lead vehicle’s intention to change lanes or to turn in the near future. Accordingly, the ego driver could anticipate a dissolving outcome of the situation and, thus, did not or only minimally respond to FCAs in these constellations. This assumption is underlined by a finding of an interview study (Eichelberger & McCartt, 2014). Forty-two percent of the FCA experienced drivers who previously reported to have received unnecessary alarms stated that unnecessary alarms occurred when the lead vehicle was turning. Additionally, Flannagan et al. (2016) found that alarm rates for this kind of traffic situation decreased over time. The authors assumed that drivers were able to anticipate alarms in these scenarios. Therefore, they might have adapted their behaviour to avoid setting off unnecessary alarms. In contrast, when drivers had no advantage over the system in anticipating the other road user’s behaviour, prior research showed that they responded to unnecessary alarms and indicated trust in the alarm system even though the potential conflict finally dissolved (Lees & Lee, 2007; Naujoks et al., 2015).

In conclusion, the following hypothesis is formulated.

> **Hypothesis III.** The system risk assessment is higher than drivers’ retrospective subjective hazard perception when drivers have advantages over the system in anticipating a dissolving outcome of a potential conflict. This advantage is based on drivers’ consideration of …
>
> a. … their own manoeuvre intentions.
> b. … intentions attributed to other road users.

3.1.4 Summary of Theoretical Framework

This section sums up the hypotheses derived from the theoretical framework of drivers' subjective alarm evaluation. Events that result in identical physical measurements will consistently lead to the same level of system risk assessment. However, events with identical physical conditions might result in varying levels of drivers' subjective hazard perception. An advantage of the driver over the system may arise on each level of situation awareness as soon as drivers take additional factors into account which are concurrently not considered by the system. Under the condition that a potentially critical situation dissolves in the further course, advantages of the driver over the system on one or more levels of situation awareness finally cause a discrepancy between system risk assessment and human subjective hazard perception. More specifically, the driver's hazard perception is lower than the system's risk assessment. The most important role in causing such a discrepancy is ascribed to human advantages on the anticipation level. Drivers' retrospective subjective hazard perception is hypothesised to determine their perceived need for assistance. As a consequence, drivers' current need for assistance is low and they perceive activated alarms as unnecessary.

3.2 Research Questions and Empirical Research

Based on empirical research, this thesis aimed to provide evidence for the hypotheses outlined in Section 3.1. Associated therewith, the following research questions were raised.

- Does drivers' subjective hazard perception predict their perceived need for assistance?
- Does a discrepancy between system risk assessment and drivers' subjective hazard perception render alarms perceived as unnecessary by drivers?
- Does such a discrepancy result from advantages of the driver over the system in anticipating a dissolving outcome of a potential conflict based on the consideration of …
    a. … their own manoeuvre intentions?
    b. … intentions attributed to other road users?

Additionally, the empirical research of this thesis intended to gain knowledge concerning two additional research questions which were not directly associated with the theoretical framework.

- Which factors influence drivers' acceptance of unnecessary alarms?
- How do drivers respond to unnecessary alarms?

Knowledge about the impact of unnecessary alarms on drivers’ responses and acceptance is important to assess the importance of implementing alarm activation strategies that reduce the rate of unnecessary alarms. Previous research suggested that unnecessary alarms seem to have a less negative impact on driver acceptance than false alarms (see Section 2.3.5). Insights concerning drivers’ subjective evaluations of unnecessary alarms were mainly based on interviews and focus group discussions. Therefore, each driver might have had a different interpretation of unnecessary alarms and the circumstances under which they experienced unnecessary alarms were unclear and diverse. Moreover, there were no systematic investigations that compared acceptance of correct alarms to that of unnecessary alarms. The research in this thesis aimed to examine drivers’ acceptance of unnecessary alarms compared to correct alarms. In this context, it was additionally investigated if drivers’ acceptance of unnecessary alarms differs dependent on their ability to anticipate a dissolving outcome of a potential conflict. Additionally, drivers’ acceptance of two different adaptive FCA systems that suppressed unnecessary alarms was compared to their acceptance of a conventional FCA system that activated unnecessary and useful alarms.

Results of prior driving simulator studies and naturalistic driving studies provided different results concerning the impact of unnecessary alarms on the intensity of driver responses (see Section 2.3.4). Drivers’ previous experiences with unnecessary alarms and their ability to anticipate the further course of the situation might influence the intensity of alarm responses. This thesis had the additional objective to understand if and how unnecessary alarms influence drivers’ responses in comparison to their natural driving behaviour in the same situations without alarms.

Four driving simulator studies were carried out to examine the outlined research questions. In all studies, participants encountered situations with identical physical conditions between their own vehicle and another road user (TTC values), while the outcome of the potential conflict was varied. Dependent on drivers’ own manoeuvre intentions or subsequent actions of other road users, the potential conflict either remained or dissolved within the next few seconds.

Study 1 (see Chapter 5) examined if drivers’ perceived need for assistance is predicted by their subjective hazard perception. Additionally, the study investigated if a discrepancy between system risk assessment and drivers’ subjective hazard perception renders alarms unnecessary in the eyes of the driver. To achieve this discrepancy, drivers were able to anticipate that a potential conflict would dissolve dependent on their current manoeuvre intention. The objective was to influence drivers' anticipation and, thus, drivers' subjective hazard perception. At the same time, the system's prediction based on physical measurements alone and its risk assessment remained at a constant level.

The aim of Study 2 (see Chapter 6) was to confirm and extend the findings of Study 1. In Study 1, participants experienced an open outcome of the traffic events as the simulation screen was blanked at predefined TTC values. In contrast, Study 2 examined the impact of drivers' *retrospective* subjective hazard perception on their perceived need for assistance after having encountered the entire traffic event either with or without receiving FCAs. Similar to Study 1, different manoeuvre intentions served to cause discrepancies between system risk assessment and subjective hazard perception. Moreover, acceptance ratings of alarms hypothesised to be perceived as either useful or unnecessary were analysed. Beyond subjective evaluations of collision alarms, the study elucidated short-term effects of unnecessary alarms on driver behaviour.

Study 3 (see Chapter 7) investigated if drivers' ability to anticipate intentions of other road users represents an advantage over the system on the anticipation level and results in a discrepancy between system risk assessment and drivers' subjective hazard perception. Participants encountered situations with a braking lead vehicle with identical TTC values that would have consistently activated FCAs. However, the subsequent action of the lead vehicle either resulted in a dissolving or remaining conflict. Drivers could either predict or not predict the intention of the lead vehicle's driver. One group of drivers received an FCA during each event and the other group experienced the same events without FCAs. It was assumed that drivers' ability to anticipate a dissolving outcome of a potential conflict would influence their retrospective subjective hazard perception and perceived need for assistance. Additionally, the study aimed to gain further insights into drivers' acceptance of unnecessary alarms and short-term effects of unnecessary alarms on drivers' responses.

Based on the knowledge gained by the previous three studies and theoretical considerations on the importance of mental models (see Section 2.4.3), Study 4 (see Chapter 8) evaluated two different adaptive FCA systems that considered drivers' manoeuvre intention for alarm activation. One system simply suppressed unnecessary alarms, while the other system displayed an explanatory pop-up in the HUD when alarms were suppressed. These systems were compared to a conventional non-adaptive FCA system in terms of their effects on perceived system acceptance, trust, reliability and system understanding. Furthermore, the study investigated how responses to unnecessary alarms develop with multiple exposure.

The following chapter elucidates the common methodology of the conducted studies. The four driving simulator studies are described in detail in Chapters 5 to 8. In Chapter 9, the results are taken together in a general discussion.

4 Common Methodology

This chapter describes the apparatuses and alarm systems used in the conducted studies and the dependent measures. Further descriptions of the methodology specifically used in the different studies can be found in the corresponding chapters.

4.1 Apparatuses

The four studies were conducted in two different fixed-base driving simulators of WIVW (Würzburg Institute for Traffic Sciences) GmbH (Studies 1, 3, 4) and Opel Automobile GmbH (Study 2). Both simulators used an Opel Insignia as mockup and a 5.1 Dolby surround system to provide the auditory input. The simulators used the driving simulation software SILAB of WIVW GmbH. Participants in the vehicle and the experimenter who was either located in the operator room (WIVW) or on the operator desk behind the driving simulator (Opel) communicated via intercom. The driving simulators are shown in Figure 4-1.

Figure 4-1. Fixed-base driving simulators of Opel Automobile GmbH (left) and WIVW GmbH (right).

The simulator of WIVW GmbH provided a 300° horizontal and 47° vertical field of view. This was realized by five image channels with a resolution of 1400x1050 pixels each that seamlessly projected the simulation onto a flat screen. The rear view was furnished by two LCD displays installed as rear-view mirror and left-side mirror. Nine computers were used for simulation.

The simulator of Opel provided a 130° frontal field of view with three 70′′ thin-film transistor (TFT) screens and a full rear view offered by an additional 70′′ TFT screen (resolution 1980x1080 pixels) visible through a conventional rear-view mirror and by two 7′′ TFT screens (800x480 pixels) as side mirrors. Thirteen computers were used for simulation.

In Studies 2, 3, and 4, participants answered intermediate questionnaires on a tablet that was positioned on the front passenger seat while driving. For Study 2, we used an 8′′ Samsung tablet (model SM-T310, Android) to present the questionnaires and the software LimeSurvey (Limesurvey GmbH, 2012) for programming. For Study 3 and 4, the questionnaires were programmed with the software Qualtrics (Qualtrics, 2017) and were presented on an 8′′ Samsung tablet (model Galaxy 3, Android).

4.2 Alarm System

All conducted studies investigated collision alarms provided by an FCA system. The nature and modality of the FCAs have been kept constant between the studies. The imminent visual-auditory FCA consisted of five urgent high-pitched beeps (5 x 100 milliseconds on/off, 2,000 Hz) and a flashing red LED segment at the bottom of the windshield (5 x flashing 1,000 ms). The FCA was visual-auditory because previous research demonstrated that multimodal alarms favoured fast reaction times and response accuracy (Ho et al., 2007; Liu & Jhuang, 2012; Reinmueller et al., 2018). Moreover, visual-auditory FCAs are used for most conventional FCA systems available in present-day vehicles. The naturalistic driving studies that provided insights into high rates of unnecessary FCAs also mainly used FCA systems with visual-auditory alarms (Flannagan et al., 2016; General Motors Corporation, 2005). The visual component of the FCA was chosen as this type of visual FCA led to the fastest alarm detection time in a study by Perez et al. (2009) compared to other visual FCAs (see Section 2.2.2). It is illustrated by HUD-10 in Figure 2-2. In the conducted studies, the FCAs were either triggered by braking lead vehicles or by other road users that were approaching the ego vehicle from the side. Therefore, alarm activation was associated with TTC values that fell below predefined critical thresholds. As shown in Equation 1, the TTC was calculated by the distance between ego vehicle and the other road user (*d*) divided by their relative velocity (v_{rel}) (Janssen & Nilsson, 1991).

$$TTC = \frac{d}{v_{\mathrm{rel}}} \qquad (1)$$

For scenarios with a crossing road user, the velocity of the other road user has been included in the TTC equation with the value zero (Figure 4-2). In these cases, the TTC was calculated by the distance between two road users divided by the velocity of the ego vehicle.

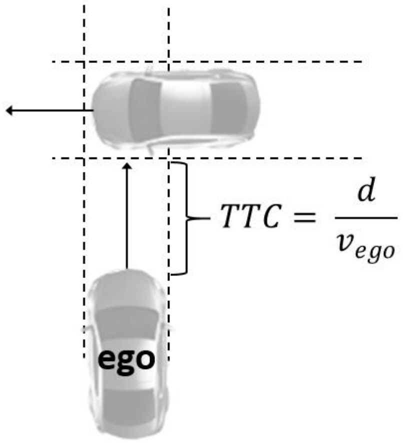

Figure 4-2. Calculation of the TTC with a crossing road user. ego = ego vehicle.

Only in Study 1, the so-called ETTC (Enhanced TTC) was calculated for scenarios with a braking lead vehicle. The ETTC equation (Equation 2) additionally considered the relative deceleration between ego and lead vehicle (D_{rel}) (Winner et al., 2015). In the other studies, for technical reasons the used FCA systems could only be controlled by the TTC without a consideration of the relative deceleration.

$$ETTC = \frac{\sqrt{v_{\text{rel}}^2 + 2D_{\text{rel}}d - v_{\text{rel}}}}{D_{\text{rel}}} \tag{2}$$

4.3 Dependent Measures

This section provides a description of dependent measures that were assessed in more than one of the conducted studies.

To measure subjective hazard perception, we used the Situation Criticality Scale by Neukum, Krüger, Mayser, and Steinle (2008). It is a category sectioning scale that was developed to evaluate the criticality of driving and traffic situations. Participants were asked to evaluate each event with this scale consisting of verbal categories that are further subdivided into numerical scale points. The scale was introduced by the statement “Evaluate the situation, please. The situation was ...”. Participants needed to choose a verbal category first and to further refine their chosen category with the numerical scale point. As illustrated in Figure 4-3, these categories are 0 = *not noticeable*, 1–3 = *harmless*, 4–6 = *uncomfortable*, 7–9 = *dangerous*, and 10 = *not controllable*. Participants received an instruction on the meaning of each verbal category. Situations in which the driving task requires no or almost no effort should be evaluated as harmless. In uncomfortable situations, drivers must take significant but still tolerable effort to accomplish the driving task. Situations are dangerous if they are very demanding and the criticality associated with the situation is not perceived as tolerable anymore. If situations lead to a subjective or objective loss of control over the vehicle, they should be evaluated as not controllable. The instruction contained a clear cut-off criterion concerning driving safety. Situations that are evaluated up to the 6th scale point are still acceptable for driving and traffic safety, while ratings from the 7th scale point on are not.

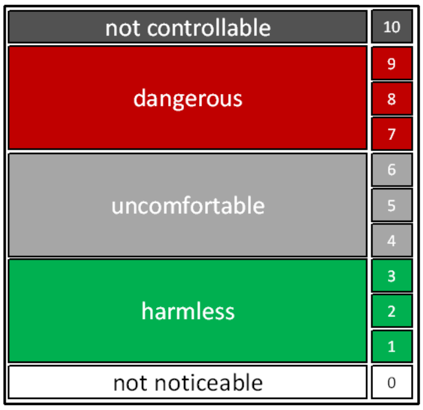

Figure 4-3. Situation Criticality Scale by Neukum et al. (2008).

Alarm acceptance was measured with the usefulness subscale of the acceptance questionnaire by van der Laan, Heino, and de Waard (1997). The items were introduced by the statement “Please evaluate the collision warning in this traffic situation. The warning was…” and were measured on a 5-point sematic differential scale. Originally, the scale consists of five items (*useful – useless*; *nice – annoying*; *effective – superfluous*; *assisting – worthless*; *raising alertness – sleep-inducing*). As a previous study showed that the item “raising alertness – sleep-inducing” yielded insufficient discrimination power when being used in the alarm context, the studies of this thesis excluded this item.

To measure driver responses to the test events including a braking lead vehicle, the magnitude of speed reduction and maximum deceleration were measured. The recording of the driving data started when the lead vehicle initiated to decelerate and stopped when the ego driver re-accelerated. In case the ego-driver did not decelerate during the test event, data recording stopped at a predefined position in the test scenario. The magnitude of speed reduction was calculated as a result of the speed participants drove when the lead vehicle started braking minus their lowest speed before they re-accelerated or their speed at the predefined position in the scenario (in km/h). The maximum deceleration represents the lowest acceleration value after the lead vehicle started braking and before the participant re-accelerated or the predefined position was reached in the scenario (in m/s²).

5 Study 1: Perceived Need for Assistance[1]

5.1 Introduction and Research Questions

In prior research on adaptive driver assistance systems, adaption parameters were selected based on their hypothesised impact on drivers' need for assistance. So far, no previous study has systematically investigated which factors actually predict drivers' perceived need for assistance. Identifying such factors might gain insights why drivers perceive certain alarms as unnecessary. The current study specifically investigated drivers' perceived need for assistance in potential collision situations by addressing the following research questions (see Section 3.2).

- Does drivers' subjective hazard perception predict their perceived need for assistance? (Number 1 in Figure 5-1)
- Does a discrepancy between system risk assessment and drivers' subjective hazard perception render alarms perceived as unnecessary by drivers? (Number 2 in Figure 5-1)
- Does such a discrepancy result from advantages of the driver over the system in anticipating a dissolving outcome of a potential conflict based on the consideration of their own manoeuvre intentions? (Number 3 in Figure 5-1)

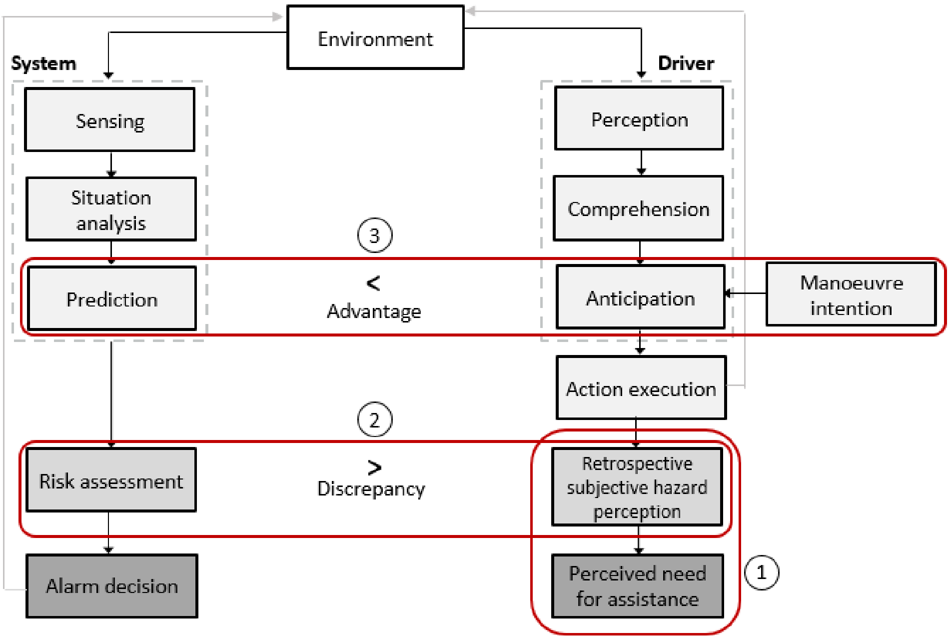

Figure 5-1. Theoretical framework of drivers' subjective alarm evaluation with research questions investigated in Study 1.

---

[1] Parts of Chapter 5 have been published in Kaß, Schmidt, and Kunde (2018a).

Hypothesis I derived from the theoretical framework of drivers' subjective alarm evaluation (see Section 3.1) proposed that drivers' perceived need for assistance is determined by their subjective hazard perception of the encountered traffic situation. Therefore, this study investigated if drivers' perceived need for assistance is primarily predicted by system risk assessment based on physical measurements or by their subjective hazard perception. It was assumed that not every situation that is evaluated as critical by the system necessarily leads to a high subjective hazard perception. Furthermore, it was hypothesised that a discrepancy between system risk assessment and drivers' subjective hazard perception leads to alarm activations while the driver has a low need for assistance (Hypothesis II in Section 3.1). As a consequence, drivers would conceivably perceive an activated alarm as unnecessary. In addition, the study examined how such a discrepancy between system risk assessment and drivers' subjective hazard perception can arise. Present-day FCA systems use alarm activation algorithms that base predictions about crash likelihood on physical measurements alone. As soon as TTC values fall below a predefined critical threshold, the system predicts a high crash likelihood. This prediction leads to a high risk assessment and would result in an alarm activation. In contrast, human anticipation presumably takes into account drivers' own manoeuvre intention as additional factor (see Section 2.1.2.4). Dependent on the current manoeuvre intention, the same environmental event, such as a braking lead vehicle, can result in different outcomes of the potential conflict. The anticipation of a remaining or a dissolving outcome of a potential conflict might result in different levels of subjective hazard perceptions and perceived need for assistance. Concurrently, the system does not consider this factor for its prediction. Therefore, human anticipation is assumed to have an advantage over system's prediction (Hypothesis IIIa in Section 3.1). A potential conflict with another road user that causes a low TTC value but finally dissolves because of the driver's manoeuvre intention is assumed to be perceived as non-hazardous by the driver, while evaluated as critical by the FCA system. To sum up, it was assumed that alarms are perceived as not needed by drivers due to a discrepancy between system risk assessment determined by the TTC-based prediction of crash likelihood and drivers' subjective hazard perception based on the anticipation of crash likelihood additionally influenced by the current manoeuvre intention.

To test these assumptions, a mediation hypothesis (1) and a moderated mediation hypothesis (2) were proposed. The corresponding model is shown in Figure 5-2.

Hypothesis 1. Drivers' subjective hazard perception of the encountered traffic scenario will mediate the positive relationship between system risk assessment and drivers' perceived need for assistance.

Hypothesis 2. Manoeuvre intention will moderate the strength of the indirect relationship between system risk assessment and drivers' perceived need for assistance via drivers' subjective hazard perception, such that the mediating effect is expected to only be salient when the traffic event interferes with the intended manoeuvre.

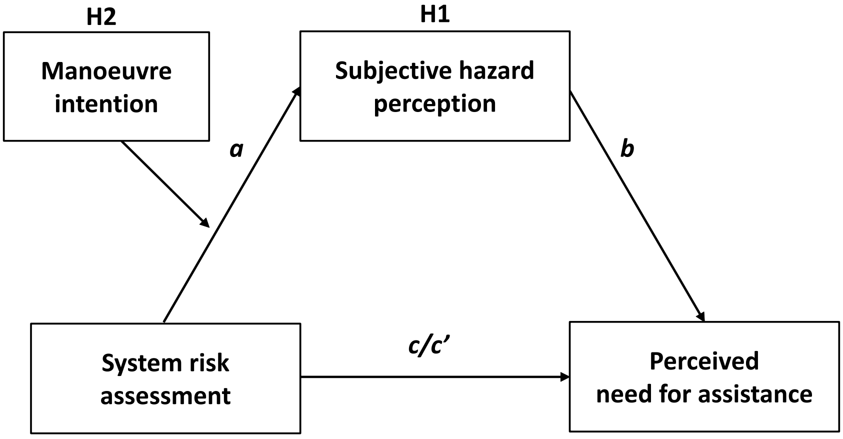

Figure 5-2. Moderated mediation model investigated in Study 1. H1 = Hypothesis 1, H2 = Hypothesis 2.

5.2 Method

5.2.1 Participants

A total of 30 participants (15 female, 15 male) took part in the study. Participants were between 22 and 73 years old (*M* = 44.07, *SD* = 15.36). Participants stated to cover *M* = 21,539 kilometres per year (*SD* = 17,267) and to have held their driver's license for *M* = 25.8 years (*SD* = 14.4). On average, they had medium prior experience with FCA systems, *M* = 3.33, *SD* = 1.73 on a 5-point Likert scale (1 = *very little*, 2 = *little*, 3 = *medium*, 4 = *much*, 5 = *very much experience*). Medium experience means that participants have already personally experienced at least one collision alarm either in their own or in another car. Participants were recruited from the WIVW driver test panel. Each of them had received at least four hours simulator training in two training sessions (Hoffmann, Krüger, & Buld, 2003). This training includes special exercises on braking, steering, driving on the motorway, and turning at intersections. The probability of simulator sickness and, therefore, the drop out-rate can be successfully reduced with the training (Hoffmann & Buld, 2006).

5.2.2 Apparatus

The study was conducted in the driving simulator at WIVW GmbH (see Section 4.1).

5.2.3 Experimental Design

The experiment used a repeated measures design with system risk assessment and manoeuvre intention as independent factors both with two levels. Low system risk assessment (a) was operationalized by high or infinite TTC values that would not result in alarm activations of present-day FCA systems. High system risk assessment (b) was represented by low TTC values that would usually trigger alarms in present-day FCA systems (TTC values are shown in Table 5-1). To manipulate manoeuvre intention, a navigation system provided auditory and visual announcements. Dependent on participants' current manoeuvre intention, the encountered traffic event either interfered (a) or did not interfere (b) with their executed driving manoeuvre (Figure 5-3). In the latter case, the other involved road user could not cause a collision and the conflict dissolved. To reduce carry-over from one event to another, and to increase the number of measurement points, participants experienced all factor combinations within six different traffic scenarios (see Section 5.2.4). Thus, all participants encountered 24 traffic events throughout the experiment that varied according to system risk assessment and manoeuvre intention. To control for transition effects, we permutated the sequence of the 24 events to five different sequences. Each of the five sequences consisted of four blocks. The blocks contained one representative of each of the six traffic scenarios. In each block, all possible factor combinations of system risk assessment and manoeuvre intention were represented. However, two factor combinations were represented twice. We counterbalanced the position of the four blocks between the five different sequences as well as the position of the six scenarios within the blocks. Thereby, it was ensured that the sequence of the four factor combinations of each scenario was counterbalanced between the different sequences. To obtain groups of equal size for each sequence, subjects were quasi randomly distributed to the five sequences with a cell size of *n* = 6 drivers. This means that the number of participants randomly assigned to each sequence was limited.

5.2.4 Traffic Scenarios

We modified the Situation Awareness Global Assessment Technique (SAGAT) method by Endsley (1995) which was initially developed to measure situation awareness. The simulation screen was blanked at predefined TTC values (TTC between ego vehicle and conflict partner, Table 5-1). The intent was to achieve an open outcome of the relevant events. At the moment of blanking the screen, participants were confronted with exactly the same event in the environment with either low or high system risk assessment while only their manoeuvre intention varied. Figure 5-3 illustrates how manoeuvre intention varied within the scenarios. As soon as participants answered all questions concerning the event, the screen showed the previous scene again while the conflict partner was removed. Apart from one imminent collision alarm (modality is described in Section 4.2) that drivers experienced during the practice drive, no further alarms were issued throughout the study.

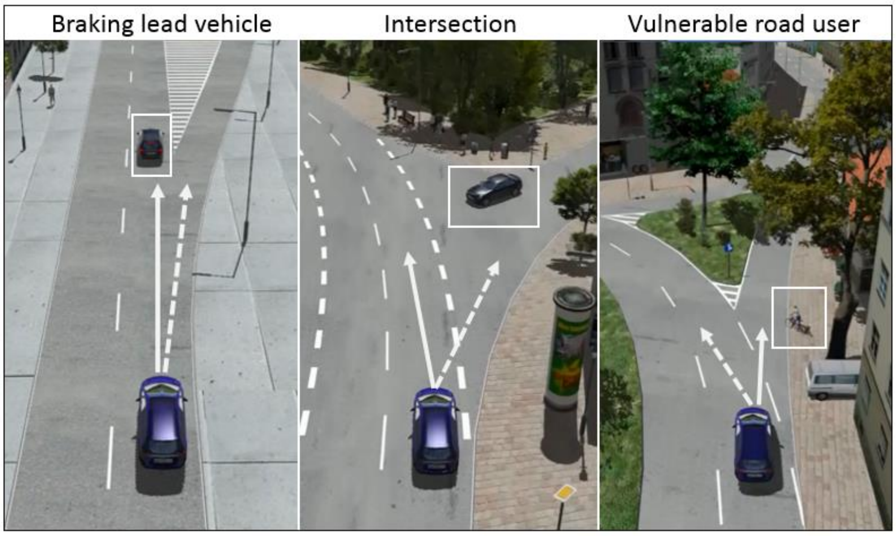

Figure 5-3. Realization of manoeuvre intention for events with high system risk assessment illustrated with one example for each of the three scenario types (braking lead vehicle, intersection, and vulnerable road user). Conflict partner is marked by a frame. Solid line: event interferes with intended manoeuvre; dashed line: event does not interfere with intended manoeuvre. For events with low system risk assessment, manoeuvre intention was realized in the same way.

The driving environment consisted of an urban setting with a speed limit of 50 km/h and evenly distributed traffic. Participants drove through intersections, roundabouts, and streets with regular turning-off streets as well as passing parked vehicles at the roadside.

The events were scripted scenarios. Participants experienced the six different traffic scenarios with each condition combination of system risk assessment and manoeuvre intention. A detailed description of the traffic scenarios and the operationalization of the independent variables system risk assessment and manoeuvre intention can be found in Table 5-1. For the calculation of the indicated TTC values in Table 5-1, we assumed an ego velocity of 50 km/h and basically used the ETTC equation (Equation 2 in Section 4.2). As relative deceleration was not applicable for the scenario types “intersection” and “vulnerable road user”, the ETTC equation transformed to the conventional TTC equation (Equation 1 in Section 4.2). As the six scenarios had different set ups, the TTC values (= moment of blanking the screen) between the scenarios could not be kept at a constant level. We gave more priority to the plausibility of the scenarios than to exactly constant TTC values between the scenarios. Ultimately, only one fourth of all events were expected to be subjectively perceived as hazardous by the drivers, in particular events with high system risk assessment in combination with an interference between event and intended manoeuvre.

Table 5-1

Description of the Six Traffic Scenarios at Two Levels of System Risk Assessment and Manoeuvre Intention

Scenario type	Traffic scenarios and conflict partner	System risk assessment		Manoeuvre intention	
Braking lead vehicle	Lead vehicle is braking, while the ego vehicle is driving behind it, there is a turning street on the right	Low	Lead vehicle decelerates slightly, TTC[a] = 11.1 s	No interference	Ego vehicle turns to the right or to the left
	Lead vehicle is braking, while the ego vehicle is driving behind it, there is a turning street on the left	High	Lead vehicle decelerates strongly, TTC[a] = 1.9 s	Interference	Ego vehicle stays behind the lead vehicle
Intersection	A motorbike is approaching the intersection from the right, while the ego vehicle is driving on the main road	Low	Motorbike/Vehicle stops at the intersection, infinite TTC[b]	No interference	Ego vehicle turns
	A vehicle is approaching the intersection from the right, while the ego vehicle is driving on the main road	High	Motorbike/Vehicle takes the ego vehicle's right of way, motorbike TTC[a] = 1.6 s, vehicle TTC[a] = 1.2 s	Interference	Ego vehicle stays on the main road
Vulnerable road user	A pedestrian is standing at the roadside at the beginning of a turning road, while the ego vehicle is driving on a bending main road	Low	The pedestrian stays at the roadside / The cyclist turns and drives along the roadside, infinite TTC[b]	No interference	Ego vehicle stays on the bending main road / in the roundabout
	A cyclist is approaching the roundabout exit from the right roadside, while the ego vehicle is driving in the roundabout	High	The pedestrian/cyclist crosses the street, pedestrian TTC[a] = 1.0 s, cyclist TTC[a] = 1.5 s	Interference	Ego vehicle turns / takes the exit on the roundabout

Note. [a] Time to collision (TTC) values are given for the moment of blanking the screen with a presumed ego velocity of 50 km/h.

[b] TCC calculation is not possible as the path of the ego vehicle and the conflict partner would not have crossed.

5.2.5 Dependent Measures

The dependent variables were drivers' ratings for subjective hazard perception and perceived need for assistance. Additionally, we asked participants to explain which precise events or objects their ratings were based on. Participants saw the corresponding items and scales printed on a piece of paper and told the experimenter their ratings and the corresponding explanation through an intercom. As described in Section 4.3, subjective hazard perception was assessed with the Situation Criticality Scale by Neukum et al. (2008). As subjects did not experience the outcome of the traffic events, the scale was introduced by a slightly modified statement “Evaluate the situation, please. The situation *is*..” (instead of *was*).

Perceived need for assistance was measured by one item that was introduced with the statement “In this traffic situation, I would like to be warned by a driver assistance system”. Participants answered this item on a category sectioning scale with five categories with the verbal labels 1—3 = *disagree,* 4—6 = *rather disagree,* 7—9 = *neither agree nor disagree,* 10—12 = *rather agree,* and 13—15 = *agree*. Each category was subdivided into three scale points. Participants reported the chosen category first and refined it with the subcategory scale point (5 x 3 = 15 scale points). This method was originally developed by Heller (1985).

5.2.6 Procedure

The study was approved by the Ethics Committee of the Institute for Psychology of the Julius-Maximilians-University Würzburg. Upon arrival, participants received information about the objective of the study, expected duration, procedures, and their right to decline to participate and to withdraw from the study once participation has begun. Participants were told that the study examines drivers’ wish for system support in different traffic situations. Prior to driving, the experimenter explained that the participant was going to experience a couple of different events throughout the simulator drive and that their task was to assign a subjective rating of the event criticality as well as to indicate their need for an alarm that is intended to warn against an imminent collision. Subsequently, the experimenter explained the meaning of every single verbal category and the cut-off point of the situation criticality scale.

Participants were instructed to follow the traffic rules and to maintain a speed of 50 km/h during the drive except for turning situations. Participants drove a 10-minute practice drive that included a first traffic situation with blanked screen to get familiar with the procedure and the questions. Besides, during the practice drive participants experienced a situation in which an imminent FCA was triggered by a hard braking lead vehicle. Thereby, they should get a better idea about its nature and modality (see Section 4.2). Participants were instructed that they should base their ratings concerning perceived need for assistance on this kind of alarm. During the experiment, the study leader was in a separate control room from where she monitored the driver. When drivers drove too slowly, they were verbally reminded to accelerate to 50 km/h. Throughout the experiment, each participant encountered 24 events. Overall, the experiment took about 1.5 hours per participant. At the end of the experiment, participants were thoroughly debriefed.

5.2.7 Data Analysis

The most appropriate statistical analysis for the data of the present study was multilevel analysis. In contrast to other regression methods that assume independent observations and might have resulted in biased estimation of standard errors, multilevel analysis accounts for repeated measurements nested within individuals (Bauer, Preacher, & Gil, 2006; Ohly, Sonnentag, Niessen, & Zapf, 2010). The software package Hierarchical Linear Modelling was used (HLM Student, Version 7.01) (Raudenbush, Bryk, & Congdon, 2013). To reflect intra-individual processes, the mediator and the criterion were centred to the respective person mean (group-mean centring) (Field, Miles, & Field, 2012). This centring approach allowed removing the between-person variance from these variables, e.g. different levels of sensation seeking and risk affinity between participants that might have influenced subjective hazard perception and perceived need for assistance (Ohly et al., 2010). As predictor (system risk assessment) and moderator (manoeuvre intention) variables were experimental conditions, there was no need to centre. The predictor system risk assessment was entered into the model as a dichotomous (low and high) instead of a continuous variable because low system risk assessment in Scenarios 3, 4, 5, and 6 was not represented by a specific numeric value. In these scenarios, TTC values were infinite as the conflict partner would have never crossed the driver’s way. The measurement points of the predictor and the moderator variable on Level 1 were nested in the participants on Level 2 (Zhang, Zyphur, & Preacher, 2009).

To analyse the mediation model, a procedure for estimating and assessing lower level mediation in multilevel contexts was applied (Bauer et al., 2006). The procedure modifies common mediation analysis procedures (as suggested by Baron and Kenny, (1986)) to the multilevel context and allows to estimate the entire mediation model simultaneously. Similar to single-level mediation analysis, there needs to be a significant relation (a) between the predictor and the criterion variable, (b) between the predictor and the mediator variable, (c) between the mediator and the criterion variable, and (d) the relation between the predictor and the criterion variable needs to decrease as the mediator variable is included in the model. The model in the present study is consistent with the “1-1-1 lower mediation model” proposed by Bauer et al. (2006) because predictor (system risk assessment), mediator (subjective hazard perception), and criterion (perceived need for assistance) were measured at multiple measurement points within participants. The moderator (manoeuvre intention) was a Level 1 variable as well. A random intercept model with random slopes was calculated (Bauer et al., 2006). Participants were considered as random variable.

As a prerequisite for moderated mediation analysis, it was checked if there was a significant interaction between the predictor and the moderator in predicting the mediator (Hayes, 2015; Muller, Judd, & Yzerbyt, 2005). As primary moderated mediation analysis, it was tested if the two levels of manoeuvre intention had different conditional indirect effects on the examined mediation model (Muller et al., 2005). In other words, it was analysed if the strength of the indirect effect depends on the level of the moderator variable. Therefore, measurements were split into two subgroups that represented the two levels of the moderator variable and the mediation analysis approach by Bauer et al. (2006) was repeated separately for both subgroups (Wegener & Fabrigar, 2000). One can conclude that mediation is moderated when the indirect effects differ between the two subgroups (Wegener & Fabrigar, 2000).

To verify the use of multilevel regression analysis, the intraclass correlations (ICC) on the basis of the intercept-only models were calculated (for each of the Level 1 dependent variables). The intraclass coefficient indicates the relation between the Level 1 variance within a person and the total variance of Level 1 and 2 (Eid, Gollwitzer, & Schmitt, 2017). Thus, a high ICC verifies the application of multilevel analysis because there is variability between the different participants. The ICC for need for assistance, as well as for subjective hazard perception was .09, indicating that 9 % of the variance in perceived need for assistance and subjective hazard perception was due to between-person differences.

Participants' data were excluded from data analysis if their rating explanations did not include the relevant conflict partner (see Section 5.2.5). In these cases, ratings were based on different situations than those of the other participants. In the two traffic events with vulnerable road users that did not interfere with drivers' intended manoeuvre, many participants did not mention the pedestrian or bicyclist in their explanations. They were probably not noticed by the participants, as they were not very salient and participants focused their visual attention into the direction they intended to drive. The multilevel approach can cope with missing data

(Hox, 2010; Raudenbush, Bryk, Cheong, Congdon, & Du Toit, 2011). Table 5-2 displays the remaining measurement points that were considered in the further reported analyses.

Table 5-2

Overview of Remaining Measurement Points in the Different Traffic Scenarios Grouped by System Risk Assessment and Manoeuvre Intention

		Low system risk assessment		High system risk assessment	
		No manoeuvre interference	Manoeuvre interference	No manoeuvre interference	Manoeuvre interference
Scenario type	Scenario	*n*	*n*	*n*	*n*
Braking lead vehicle	Turn right	27	29	30	30
	Turn left	28	30	28	29
Intersection	Motorbike	28	30	29	30
	Vehicle	30	30	28	28
Vulnerable road user	Pedestrian	15	29	14	30
	Cyclist	28	29	16	30
Sum of remaining measurement points = 655		∑ = 156	∑ = 177	∑ = 145	∑ = 177

5.3 Results

5.3.1 Descriptives

The data structure consisted of 24 measurement points that were nested within 30 participants, $n = 655$ measurement points remained for data analysis. Figure 5-4 displays means and 95 % confidence intervals for the dependent variables subjective hazard perception and perceived need for assistance grouped by scenario type, system risk assessment and manoeuvre intention. There was a significant positive correlation between the variables subjective hazard perception and need for assistance, $r(653) = .87$, $p < .001$.

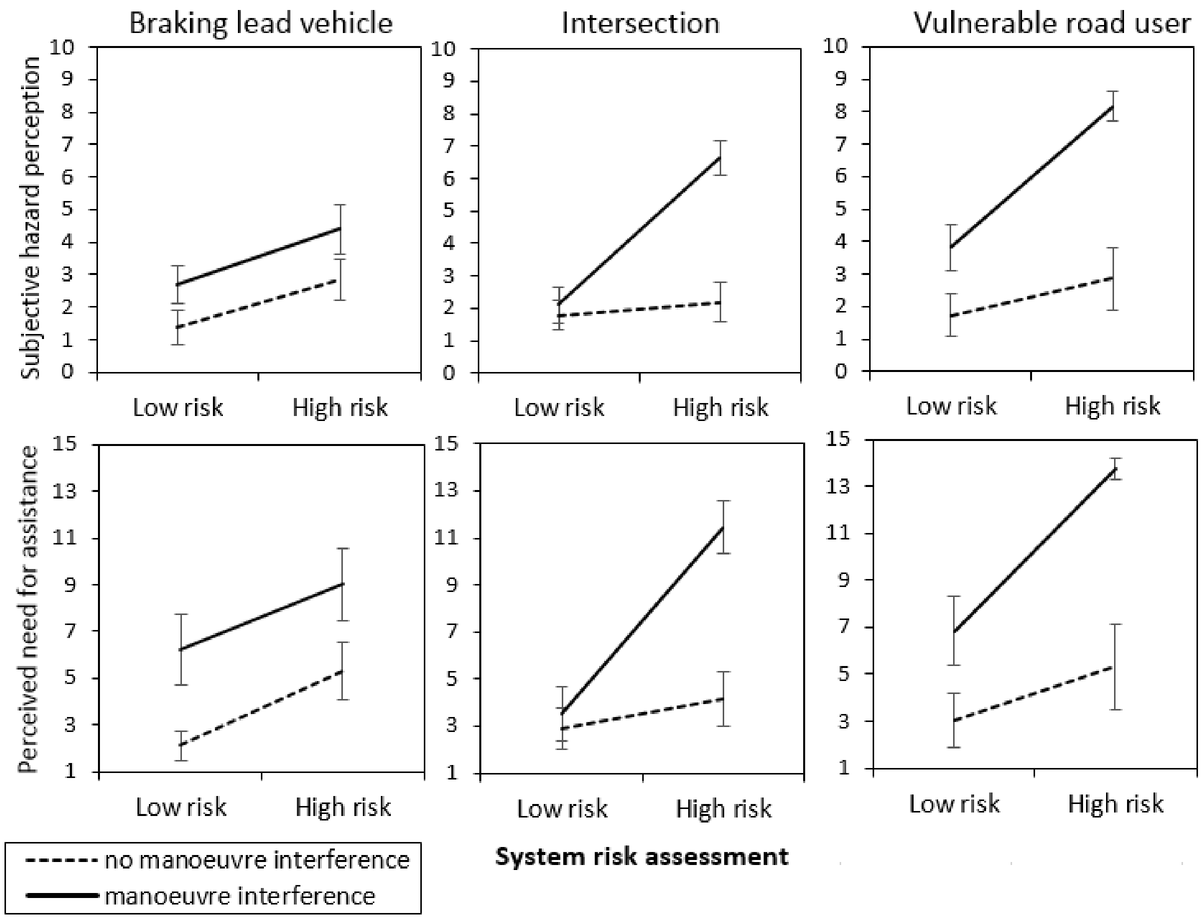

Figure 5-4. Means of subjective hazard perception (upper part) and perceived need for assistance (lower part) grouped by scenario type, system risk assessment, and manoeuvre intention. Error bars display 95 % confidence intervals.

5.3.2 Mediation Analysis

The first hypothesis assumed that system risk assessment would predict drivers' perceived need for assistance via subjective hazard perception. As a first step, the direct effect of the predictor on the criterion without taking the mediator into account was calculated (path c in Figure 5-2). Results showed that perceived need for assistance was positively associated with system risk assessment, *B* = 4.33, *SE* = 0.38, *p* < .001. On the basis of the procedure for mediation in multilevel models suggested by Bauer et al. (2006), all parts of the mediation model were tested simultaneously. With regard to the effect between predictor and mediator (path a in Figure 5-2), system risk assessment was positively related to subjective hazard perception, *B* = 2.44, *SE* = 0.19, *p* < .001. Additionally, there was a positive relationship between the mediator and the criterion variable (path b in Figure 5-2). Subjective hazard perception significantly predicted need for assistance, *B* = 1.62, *SE* = 0.06, *p* < .001. Furthermore, the results showed the adjustment of the direct effect between the predictor and the criterion when including the mediator into the model (path c' in Figure 5-2). Having taken subjective hazard perception into account, the direct effect between system risk assessment and perceived need for assistance became non-significant (*B* = 0.39, *SE* = 0.25, *p* = .126) which indicates complete mediation. The random indirect effect via subjective hazard perception was significant, *B* = 3.93, *SE* = 0.34, *Z* = 11.43, *p* < .001. Therefore, the first hypothesis was supported. Direct, indirect, and total effects are displayed in Table 5-3.

Table 5-3

Multilevel Regression Analysis for Hypotheses 1 and 2

Model/Effects	*B*	*SE*	95 % CI
Model with mediator			
Direct effect	0.39	0.25	[-0.1, 0.9]
Indirect effect	3.93***	0.34	[3.3, 4.6]
Total effect	4.33***	0.38	[3.6, 5.1]
Conditional mediation Model 1: no manoeuvre interference			
Direct effect	0.48†	0.24	[0, 1]
Indirect effect	1.71***	0.4	[0.9, 2.5]
Total effect	2.2***	0.51	[3.19, 4.35]
Conditional mediation Model 2: manoeuvre interference			
Direct effect	0.83†	0.43	[0, 1.7]
Indirect effect	5.14***	0.44	[4.3, 6]
Total effect	5.98***	0.46	[5.1, 6.9]

Note. *N* = 30 participants at Level 2, *n* = 655 measurement points at Level 1 for the models with and without mediator, *n* = 301 for conditional mediation model 1, *n* = 354 for conditional mediation model 2. Predictor is system risk assessment, mediator is subjective hazard perception, criterion is perceived need for assistance, and moderator is manoeuvre intention. CI = Confidence Interval [lower limit, upper limit].
†*p* < .10. **p* < .05. ***p* < .01. ****p* < .001.

5.3.3 Moderated Mediation Analysis

Hypothesis 2 predicted that the indirect effect via subjective hazard perception would occur only on condition that the traffic event interfered with the current manoeuvre intention (Figure 5-2). A necessary requirement to test the moderated mediation analysis was a significant prediction of the mediator (subjective hazard perception) by the interaction of the predictor (system risk assessment) and the moderator (manoeuvre intention). When manoeuvre intention as a moderator was added to path a, the interaction term for system risk assessment with manoeuvre intention significantly predicted subjective hazard perception, *B* = 2.55, *SE* = 0.33, *p* < .001. As an additional step, to ensure appropriate conclusions in case the moderated mediation analysis would be significant, it was tested whether the interaction of subjective hazard perception (mediator) and manoeuvre intention (moderator) was significant in predicting perceived need for assistance (criterion). There was no significant interaction, *B* = -0.14, *SE* = 0.09, *p* = .127. These results suggest that there were compensating effects of manoeuvre intention for system risk assessment in predicting subjective manoeuvre intention. As demonstrated in Figure 5-5, the positive relationship between system risk assessment and subjective hazard perception was stronger when the intended driving manoeuvre interfered with the encountered traffic event. These results justified calculating a multilevel moderated mediation analysis as suggested in Hypothesis 2.

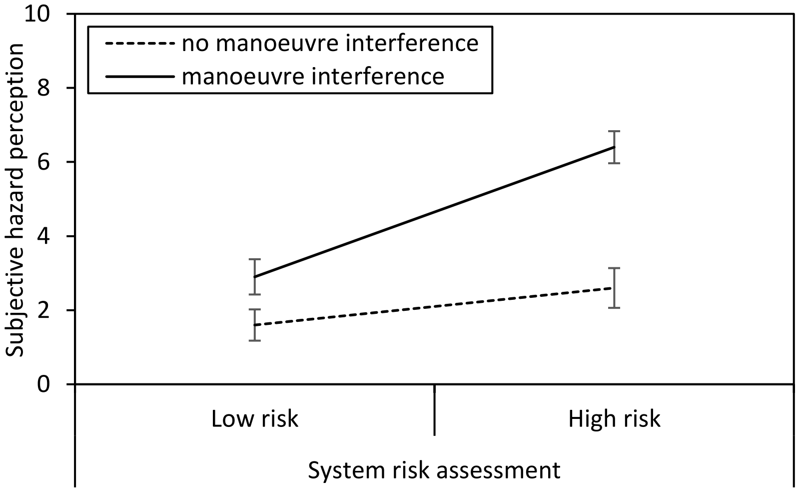

Figure 5-5. Moderating effect of manoeuvre intention on the relationship between system risk assessment and subjective hazard perception. Error bars display 95 % confidence intervals.

To test this hypothesis, the mediation analysis was repeated separately for both subgroups of the moderator variable manoeuvre intention (Wegener & Fabrigar, 2000).

Figure 5-6 illustrates the mediation models for each subgroup of manoeuvre intention. The first part of the analysis tested the conditional indirect effect for the condition that the traffic event did *not* interfere with drivers' current manoeuvre intention and, thus, the potential conflict dissolved (*n* = 301 measurement points). Inconsistent with Hypothesis 2, the results showed that subjective hazard perception emerged as a significant mediator for the effect of system risk assessment on drivers' perceived need for assistance. When the traffic event did not interfere with the intended manoeuvre, the direct effect between system risk assessment and perceived need for assistance was marginally significant, when subjective hazard perception was included in the model (path c’, *B* = .48, *SE* = 0.26, *p* = .074), indicating partial mediation. There was a significant conditional random indirect effect, *B* = 1.71, *SE* = 0.4, *Z* = 4.23, *p* < .001.

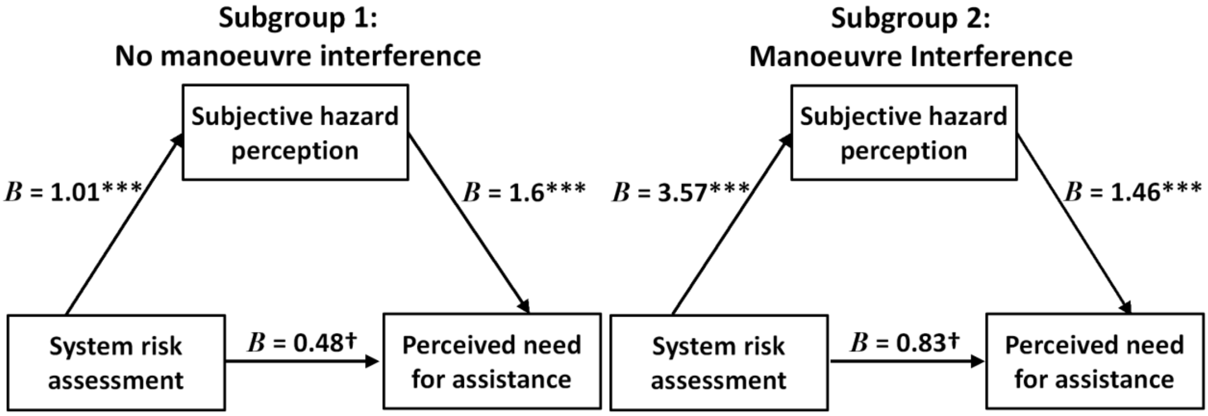

Figure 5-6. The relationship between system risk assessment and perceived need for assistance mediated by subjective hazard perception, as a function of manoeuvre intention that either does not interfere with the event (left) or that interferes with the event (right). Subgroup 1: *n* = 301; Subgroup 2: *n* = 354.
†*p* < .10. **p* < .05. ***p* < .01. ****p* < .001.

The second part of the analysis tested the conditional indirect effect when the traffic event interfered with drivers’ current manoeuvre intention and, therefore, the conflict remained (*n* = 354 measurement points). On that condition, the direct effect between system risk assessment and perceived need for assistance was partially mediated by subjective hazard perception, path c’: *B* = 0.83, *SE* = 0.43, *p* = .060. The conditional random indirect effect was highly significant, *B* = 5.14, *SE* = 0.44, *Z* = 11.66, *p* < .001. As illustrated in Figure 5-7, the non-overlapping confidence intervals of the two conditional indirect effects indicate that the mediated relationship was significantly stronger when the critical traffic event interfered with the intended manoeuvre than without interference. Table 5-3 presents the conditional direct, indirect, and total effects for the reported moderated mediation analysis.

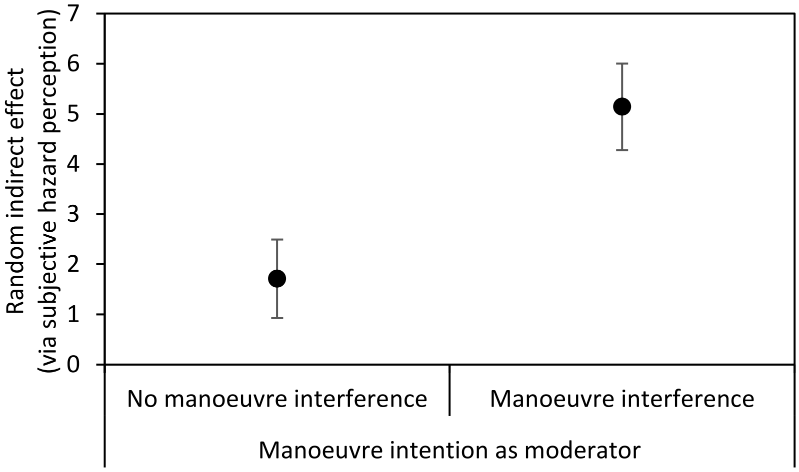

Figure 5-7. Conditional random indirect effects of the mediation model for both subgroups of the moderator variable manoeuvre intention. Error bars display 95 % confidence intervals.

The significant interaction between system risk assessment and manoeuvre intention in predicting subjective hazard perception and the conditional indirect effects were partly consistent with Hypothesis 2. Manoeuvre intention moderated the strength of the indirect relationship between system risk assessment and drivers' perceived need for assistance via drivers' subjective hazard perception. Notwithstanding Hypothesis 2, the mediating effect was also salient when there was no interference between the traffic event and drivers' manoeuvre intention. The results revealed that the mediating effect was significantly stronger when the event interfered with the intended manoeuvre than when it did not interfere.

Even though there were no a priori hypotheses regarding differences between the three implemented scenario types, a supplementary analysis included scenario type as random variable in our model. The results revealed that the interaction term between system risk assessment and manoeuvre intention significantly predicted subjective hazard perception in the scenario types intersection ($B = 4.2$, $SE = 0.48$, $p < .001$) and vulnerable road user ($B = 3.19$, $SE = 0.53$, $p < .001$), while it was not significant for the braking lead vehicle scenario type ($B = 0.11$, $SE = 0.44$, $p = .810$).

5.4 Discussion

The goal of the first study was to gain insights into factors that influence drivers' perceived need for assistance in potential collision situations. For this purpose, the study aimed to provide evidence for three hypotheses derived from the theoretical framework of drivers' subjective alarm evaluation (Figure 5-1). Therefore, 30 participants encountered six different traffic scenarios that would either result in low or high system risk assessment. Each scenario was experienced with two different manoeuvre intentions to vary the anticipated outcome of the potential conflict.

The results supported the first hypothesis and revealed that system risk assessment positively influenced subjective hazard perception which was, in turn, positively related to perceived need for assistance. This finding showed that drivers' subjective hazard perception regarding the encountered traffic event was the central factor that influenced perceived need for assistance, instead of system risk assessment that is exclusively determined by a prediction based on physical criteria. As proposed by the theoretical framework, drivers' perceived need for assistance was predicted by their subjective hazard perception (Number 1 in Figure 5-1). This finding is in line with prior research concerning the effectiveness of static product warnings (Laughery & Wogalter, 2006; Wogalter et al., 1991) and reported driver needs and alarm usefulness in the context of driver assistance (Eichelberger & McCartt, 2014; LeBlanc et al., 2006b; Portouli et al., 2006; van Driel & van Arem, 2005).

To investigate the assumption that an advantage of the driver over the system on the anticipation level (Number 3 in Figure 5-1) causes a discrepancy between system risk assessment and drivers' subjective hazard perception (Number 2 in Figure 5-1), drivers encountered identical traffic events with different manoeuvre intentions. The present study effectively examined the direct impact of drivers' manoeuvre intention on subjective hazard perception of traffic events with identical physical measurements. Accordingly, Hypothesis 2 suggested that the mediating effect of subjective hazard perception would only be present when the traffic event interfered with the intended manoeuvre and, thus, the potential conflict remained. The results concerning this moderating effect of manoeuvre intention were not completely consistent with this hypothesis. The analysis revealed that even when the current manoeuvre intention caused a dissolving outcome of the potential conflict, events with high system risk assessment were perceived as more hazardous than events with low system risk assessment. However, manoeuvre intention determined the strength of the relationship between system risk assessment and subjective hazard perception. An event with high system risk assessment was subjectively perceived as more hazardous when the manoeuvre intention led to the anticipation of a remaining than a dissolving outcome of the potential conflict. Hence, the mediated relationship was found to be stronger. Extending previous surveys and exploratory studies about necessity and usefulness of driver assistance (LeBlanc et al., 2006a; Portouli et al., 2006; van Driel & van Arem, 2005), this finding reveals that a discrepancy between a pure TTC-based system risk assessment and drivers’ subjective hazard perception of the same traffic event (high system risk assessment and low subjective hazard perception) could lead to alarms perceived as not needed by drivers (Number 2 in Figure 5-1). As soon as an encountered traffic event with a low TTC did not interfere with drivers’ current manoeuvre intention, their subjective hazard perception was lower than system risk assessment. Consequently, this discrepancy was caused by an advantage of the driver over the system at the anticipation level (Number 3 in Figure 5-1).

It should be considered that subjective driver ratings might have been influenced by speculations. The method of blanking the simulation screen caused that participants based their ratings on an imagined forecast of what could have happened instead of a real experience. This may explain the observation that the mediated relationship between system risk assessment and perceived need for assistance via subjective hazard perception was lower but still present under the condition that the traffic event did not interfere with the planned manoeuvre. Particularly, the evaluation of subjective hazard perception and perceived need for assistance might have been influenced by participants’ thought that the event would have been hazardous *if* they had had a different manoeuvre intention. Furthermore, evaluations of subjective hazard perception and perceived need for assistance differed between scenario types (Figure 5-4). For example, events with vulnerable road users at low system risk assessment led to higher ratings of subjective hazard perception and perceived need for assistance compared to other events involving another car as conflict partner. These events were probably perceived as more hazardous because a collision with a vulnerable road user would have had more severe consequences than with another car. The scenarios with braking lead vehicles differed from the other scenario types in two respects. First, events with high system risk assessment that interfered with drivers’ manoeuvre intention resulted in lower ratings for hazard perception and need for assistance than the other scenarios. Second, manoeuvre intention did not moderate the effect of system risk assessment on subjective hazard perception. The reason for the first difference might be twofold. On the one hand, the outcome of the scenario types intersection and vulnerable road users were dependent on both drivers’ own manoeuvre intentions and those of other road users arriving from the side. Therefore, participants might have perceived less control over the outcome of these events than in a situation with a braking lead vehicle. On the other hand, the method of blanking the screen might have caused a misjudgement of the magnitude of deceleration of the braking lead vehicle. This methodological limitation might also explain the finding that manoeuvre intention had no moderating effect in scenarios with a braking lead vehicle. As the screen was blanked shortly after the lead vehicle initiated its braking manoeuvre, participants might have underestimated the risk to collide with the hard braking vehicle ahead and overestimated the risk to collide with a slightly braking lead vehicle. The brake light onset in combination with only the initial part of the braking manoeuvre of the lead vehicle might not have contained enough information about the intensity of the braking manoeuvre (Morando et al., 2016). In general, it must be considered that drivers' subjective hazard perception and perceived need for assistance might not always match reality. Humans tend to misjudge the real risk of situations (Charlton, Starkey, Perrone, & Isler, 2014; Groeger & Chapman, 1990; Watts & Quimby, 1980) and their own abilities (Kruger & Dunning, 1999). Therefore, drivers might perceive some alarms as accurate in retrospect which they would have considered as unnecessary in advance (Lees & Lee, 2007). Future work should examine differences for subjective hazard perception and perceived need for assistance dependent on the time of measurement (either before or after experiencing the corresponding traffic event). Related to the outlined limitations, Study 2 examined the impact of retrospective subjective hazard perception on drivers' perceived need for assistance after drivers had encountered the entire traffic event.

5.5 Conclusion

Based on assumptions derived from the theoretical framework of drivers' subjective alarm evaluation (Figure 5-1), Study 1 provided insights into psychological factors and processes that have an impact on drivers' perceived need for assistance in potential collision situations. Multilevel analyses revealed that drivers' subjective hazard perception of the encountered traffic event mediated the relationship between system risk assessment and drivers' perceived need for assistance. The current manoeuvre intention influenced the strength of this mediated relationship, as the mediation was stronger when the intended driving manoeuvre caused a remaining outcome of the conflict with another road user than a dissolving outcome of the potential conflict.

To sum up, the results of Study 1 provided evidence for Hypotheses I, II, and IIIa derived from the theoretical framework (see Section 3.1). Drivers' perceived need for assistance was primarily predicted by their subjective hazard perception. While the prediction level of conventional FCA systems is exclusively based on the current TTC measurement, the results of the present study indicated that drivers' anticipations of the outcome of a complex driving situation differ depending on their current manoeuvre intention. Consequently, the same environmental event could result in a discrepancy between system risk assessment and drivers' subjective hazard perception. As drivers' perceived need for assistance increased with increasing subjective hazard perception, alarm activation strategies that disregard drivers' current manoeuvre intention would provide collision alarms subjectively perceived as unnecessary under the following circumstances: The TTC between ego vehicle and conflict partner is low, while the driver's current manoeuvre intention causes a dissolving outcome of the potential conflict. Based on the system's prediction of a high crash likelihood due to the low TTC, a high system risk assessment triggers an alarm, while the same event is perceived as non-hazardous by the driver. Therefore, the driver would perceive this alarm as not needed.

6 Study 2: Retrospective Subjective Hazard Perception[2]

6.1 Introduction and Research Questions

Study 2 addressed several research questions. First, the study aimed to extend the findings of Study 1 and to address certain ambiguities. In this context, Study 2 investigated the same research questions as Study 1 with methodological modifications (Figure 5-1).

- Does drivers' subjective hazard perception predict their perceived need for assistance? (Number 1 in Figure 5-1)
- Does a discrepancy between system risk assessment and drivers' subjective hazard perception render alarms perceived as unnecessary by drivers? (Number 2 in Figure 5-1)
- Does such a discrepancy result from advantages of the driver over the system in anticipating a dissolving outcome of a potential conflict based on the consideration of their own manoeuvre intentions? (Number 3 in Figure 5-1)

In the previous study, participants rated their perceived need for assistance and subjective hazard perception of traffic events with an open outcome. Thus, they did not experience the entire traffic event. The intent was that each driver is confronted with exactly the same event in the environment. Thereby, their ratings were not influenced by their driving performance and the actual outcome of the event. As already mentioned in Section 5.4, drivers' ratings could have been biased by speculations about an imagined forecast of the outcome of the situation. The theoretical framework proposes that drivers' perceived need for assistance is determined by their *retrospective* subjective hazard perception (see Sections 2.5 and 3.1). Drivers' subjective hazard perception during an encountered situation might be distorted by situation awareness errors. In some events in Study 1, drivers misjudged the real risk of the situation. For example, many participants underestimated the risk to collide with a hard braking lead vehicle and overestimated the risk to collide with a slightly braking lead vehicle. These misjudgements might have also been caused by the method of blanking the screen (see Section 5.4). It is assumed that the retrospective subjective hazard perception that drivers derive *after* having experienced the overall traffic situation can diverge from the hazard which they perceived *within* the encountered traffic event (see Section 2.5). With regard to the scenarios with a hard braking lead vehicle in Study 1, drivers' retrospective hazard perception could be

---

[2] Parts of Chapter 6 have been published in Kaß, Schmidt, and Kunde (2019).

higher than their hazard perception in the moment when the lead vehicle started to decelerate. For the retrospective subjective hazard perception, drivers might additionally consider the necessity to brake immediately and strongly to avoid a rear-end collision. Therefore, drivers might perceive a higher need for assistance and evaluate activated alarms as more supportive and useful than they would have expected before. As ratings for subjective hazard perception and perceived need for assistance differed between the different scenario types in Study 1, participants in Study 2 experienced only one scenario type. The braking lead vehicle scenario was chosen for different reasons. First, the outcome of the potential conflict was solely dependent on the ego driver's manoeuvre intention. Second, the method of blanking the screen might have distorted drivers' subjective evaluations of this scenario type the most in Study 1. Third, manoeuvre intention had no moderating effect in this scenario type in the previous study. Therefore, Study 2 aimed to gain further insights into the influence of manoeuvre intention on drivers' retrospective subjective hazard perception of traffic events with identical physical measurements. Using a modified methodology to be able to measure drivers' retrospective subjective hazard perceptions, a mediation hypothesis (1) and a moderated mediation hypothesis (2) were tested as in Study 1. The corresponding model is shown in Figure 6-1.

> **Hypothesis 1.** Drivers' *retrospective* subjective hazard perception of the encountered traffic scenario will mediate the positive relationship between system risk assessment and drivers' perceived need for assistance.
>
> **Hypothesis 2.** Manoeuvre intention will moderate the strength of the indirect relationship between system risk assessment and drivers' perceived need for assistance via drivers' *retrospective* subjective hazard perception, such that the mediating effect is expected to only be salient when the traffic event interferes with the intended manoeuvre.

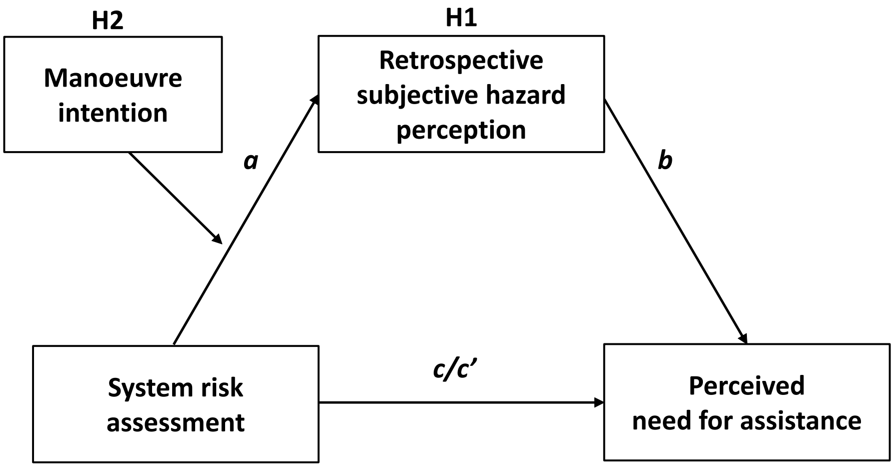

Figure 6-1. Moderated mediation model investigated in Study 2. H1 = Hypothesis 1, H2 = Hypothesis 2.

Moreover, the study addressed the research question concerning drivers’ acceptance of unnecessary alarms.

- Which factors influence drivers’ acceptance of unnecessary alarms?

This study aimed to gain insights into drivers’ acceptance of unnecessary alarms compared to their acceptance of useful alarms. Alarms were considered as unnecessary in situations with high system risk assessment (low TCC values) while drivers’ manoeuvre intention caused a dissolving outcome of the potential conflict. Under the condition that drivers’ manoeuvre intention led to a remaining conflict, alarms were considered as useful. To ensure that this classification matched drivers’ subjective evaluations of alarms, drivers were asked to classify alarms as either unnecessary or useful. By taking their current manoeuvre intention into account, drivers had an advantage over the alarm system in anticipating the outcome of the potential inter-vehicle conflict. FCAs had the potential to prevent drivers from causing a rear end collision when drivers’ manoeuvre intention interfered with the braking lead vehicle and the conflict remained. In contrast, FCAs activated in situations in which the braking lead vehicle did not interfere with drivers’ manoeuvre intention and the potential conflict dissolved would never prevent drivers from causing a collision. This line of thought leads to the third hypothesis.

> **Hypothesis 3.** In traffic situations with a hard braking lead vehicle leading to a high system risk assessment, drivers indicate a higher acceptance for alarms issued while the lead vehicle interferes with their current manoeuvre intention than without interference.

Beyond subjective evaluations, the present study elucidated short-term effects of unnecessary alarms on driver behaviour addressing the following research question.

- How do drivers respond to unnecessary alarms?

Drivers' braking responses when receiving unnecessary alarms were compared to those of drivers who experienced the same situation without alarm. As described in Section 2.3.4, previous research revealed contradictory findings concerning this research question. On the one hand, drivers are assumed to consider their current manoeuvre intention to anticipate a dissolving outcome of the situation. Thus, they are assumed to know that they will not collide with the braking lead vehicle and unnecessary alarms might cause only slight or no braking responses (Flannagan et al., 2016; General Motors Corporation, 2005). On the other hand, without prior experience with situations usually associated with unnecessary alarms, the process of validating an unnecessary alarm activated by an apparent alarm trigger (lead vehicle) might be very demanding (Gérard & Manzey, 2010). Therefore, unnecessary alarms could also cause superfluous braking responses when drivers have no or little experience with situations that usually activate unnecessary alarms (Lees & Lee, 2007). Consequently, no directed hypothesis could be derived.

6.2 Method

6.2.1 Participants

A total of 56 participants (18 female, 38 male) took part in the study. Three participants had to be excluded from data analysis, one person due to simulator sickness and two persons due to technical problems with LimeSurvey. The remaining 53 participants (16 female, 37 male) were between 23 and 60 years old ($M = 41.49$, $SD = 11.21$) and have held their driver's license for $M = 22.77$ years ($SD = 11.16$). 66 % of the participants indicated to drive their car on a daily basis and 64 % indicated to cover more than 15,000 kilometres per year. On average, drivers had medium prior experience with FCA systems, $M = 2.25$, $SD = 1.11$ on a 5-point Likert scale (1 = *very little*, 2 = *little*, 3 = *medium*, 4 = *much*, 5 = *very much experience*). However, only nine participants have gained regular experience with an FCA system in their own car. Participants were recruited from a German car manufacturer's (Opel Automobile GmbH) participant test panel consisting of company employees. As study participation took place during paid working hours, participants did not receive extra monetary compensation. Each of them took part in at least one simulator training of 15 minutes to get used to the driving simulator beforehand.

6.2.2 Apparatus

The study was conducted in the driving simulator at Opel Automobile GmbH (see Section 4.1).

6.2.3 Experimental Design

As shown in Table 6-1, the experiment used a 2x2x2 mixed design with two within-subject factors system risk assessment and manoeuvre intention and the between-subject factor level of assistance. The initial situation was the same for each test event. Participants followed the lead vehicle at 50 km/h. In the condition with low system risk assessment (a), the lead vehicle decelerated slightly with 2 m/s^2 resulting in high TTC values between ego and lead vehicle (minimal TTC values: $M = 7.16$ seconds, $SD = 1.19$) that would usually not trigger alarms in present-day FCA systems. In the condition with high system risk assessment (b), the lead vehicle decelerated strongly with 15 m/s^2. This event led to TTC values that would usually trigger alarms in present-day FCA systems (minimal TTC values: $M = 1.11$ seconds, $SD = 0.16$). The FCA system in the present study was activated by TTC values that fell below 1.9 seconds. To manipulate manoeuvre intention, a navigation system provided auditory and visual announcements. Dependent on participants' current manoeuvre intention, the lead vehicle either interfered (a) or did not interfere (b) with their executed driving manoeuvre (Figure 6-2). In the latter case, the lead vehicle could not cause a collision and the potential conflict dissolved. The factor level of assistance was represented by either receiving an FCA during each test event with a TTC value below 1.9 seconds (a) or never receiving FCAs (b) (except for one FCA during the practice drive, see Section 6.2.6). FCAs were considered as unnecessary when drivers' planned manoeuvre did not interfere with the braking lead vehicle. The used type of FCA is described in Section 4.2. Subjects were quasi randomly allocated to the two groups (with FCAs $n = 21$; without FCAs $n = 32$). The group sizes differ because the conduction of multilevel analyses required at least 30 participants in the group without FCAs (Kreft & Leeuw, 1998). For practical reasons, it was not possible to conduct the study with more than 53 participants to obtain groups of equal size.

Table 6-1

Experimental Design of Study 2 with Group Sizes

		Level of assistance[b]	
		Without FCA	With FCA
System risk assessment[a]	**Manoeuvre Intention**[a]	*n*	*n*
Low	No interference	32	21
	Interference	32	21
High	No interference	32	21
	Interference	32	21

Note. [a] Within-subject factor. [b] Between-subject factor.

Participants experienced all factor combinations of the two within-subject factors with two different traffic scenarios to reduce carry-over from one event to another and to increase the number of measurement points. To get used to the traffic scenarios, navigation system, and turning manoeuvres, participants encountered four baseline events at the beginning of the simulation drive. In these events, environments did not differ from those in the test events, but the lead vehicle continued driving and did not decelerate at a certain point (2 (manoeuvre intention) x 2 (traffic scenario) = 4 baseline events). To reduce learning effects, the four baseline events were additionally used as filler events. Thus, all participants encountered eight test events that varied according to system risk assessment, manoeuvre intention and traffic scenario (2x2x2) plus four baseline and four filler events that varied according to manoeuvre intention and traffic scenario (2x2) (16 events in total). To control for transition effects, we permutated the sequence of the eight test events to four different sequences. Each sequence started with a permutated sequence of the four baseline events. The filler events were randomly allocated between the test events. To obtain groups of equal size for each sequence, subjects were quasi randomly distributed to the four sequences with a cell size of *n* = 13 — 14 drivers. This means that the number of participants randomly assigned to each sequence was limited.

6.2.4 Traffic Scenarios

The driving environment consisted of an urban setting with a speed limit of 50 km/h and evenly distributed traffic. Participants drove through streets with regular turning-off streets, parked vehicles at the roadside, and pedestrians at the sidewalk.

Participants experienced the two different traffic scenarios with each condition combination of system risk assessment and manoeuvre intention. In both scenarios, the ego vehicle followed a lead vehicle that decelerated at a certain point while there was either a turning street on the right (Scenario 1) or a turning lane on the left (Scenario 2). Figure 6-2 illustrates the two different traffic scenarios and how they varied according to manoeuvre intention. Equation 1 in Section 4.2 served to calculate the TTC values.

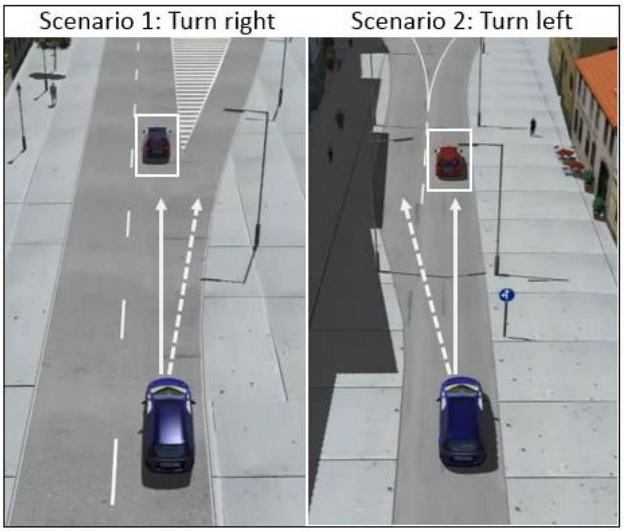

Figure 6-2. Realization of manoeuvre intention in both test scenarios. Braking lead vehicle is marked by a frame. Solid line: manoeuvre intention interferes with braking lead vehicle; dashed line: manoeuvre intention does not interfere with braking lead vehicle.

6.2.5 Dependent Measures

After each test event, participants in the group without FCAs indicated their subjective hazard perception and perceived need for assistance. In the group with FCAs, participants rated the alarm classification and acceptance after each event. As drivers received FCAs only in situations with high system risk assessment (TTC < 1.9 seconds), they did not rate alarm classification and acceptance for events with low system risk assessment. All questions were presented and answered on a tablet (see Section 4.1).

As described in Section 4.3, Situation Criticality Scale by Neukum et al. (2008) served to measure retrospective subjective hazard perception. For reasons of easier readability, the term “subjective hazard perception” will be used without “retrospective” throughout the results section of this chapter.

Perceived need for assistance was measured by one item that was introduced by the statement “In this traffic situation, I would have liked a collision warning”. Participants answered the item on a 5-point Likert scale (1 = *disagree,* 2 = *rather disagree,* 3 = *neither agree nor disagree,* 4 = *rather agree, 5 = agree*).

The measurement of alarm classification served as manipulation check. Participants were asked to decide on a binary scale whether they perceived an FCA as unnecessary or useful in the previously encountered situation (scale points: *useful*, *unnecessary*).

Alarm acceptance was only measured in the group that received FCAs. As described in Section 4.3, it was measured by using the usefulness subscale of the acceptance questionnaire by van der Laan et al. (1997). Mean internal consistency was α = .86.

To assess driver responses to the test events, the magnitude of speed reduction and maximum deceleration were measured (see Section 4.3).

6.2.6 Procedure

The Ethics Committee of the Institute for Psychology of the Julius-Maximilians-University Würzburg has declared the study to be ethically unobjectionable. Upon arrival, participants received written instructions containing information about the purpose of the study, the speed limit of 50 km/h, and an explanation of every single verbal category and the cut-off point of the situation criticality scale. They were informed that the study examines their behaviour in and their subjective evaluations of different traffic situations to gain insights into the need for collision alarms. Additionally, they signed a consent form that informed them about their right to decline to participate and to withdraw from the study at any point, and the method of data anonymization.

Participants drove a five-minute practice drive. To let them get a better idea about the nature and modality of the FCA (see Section 4.2), the practice drive included a situation in which a hard braking lead vehicle triggered an FCA. Participants in the group without FCAs were instructed that they should base their ratings concerning perceived need for assistance on this kind of alarm. The experimental drive started with the four baseline events that were not followed by questionnaires. Each test event was followed by a programmed announcement “Please stop here”. This method aimed to avoid that drivers would stop during every event with a hard braking lead vehicle as such a behaviour would have influenced driving measures. After having stopped, drivers answered questions on the tablet concerning the encountered scenario. Overall, the experiment took about one hour per participant. At the end of the experiment, participants were thoroughly debriefed.

6.2.7 Data Analysis

As in Study 1, the mediation and the moderated mediation hypotheses were tested using multilevel analysis. The models and procedures were similar to those of Study 1 described in Section 5.2.7. Intraclass correlations (ICC) were calculated on the basis of the intercept-only models for each of the Level 1 dependent variables. The ICC for need for assistance was .10 and for subjective hazard perception was .002, indicating that 10 % of the variance in perceived need for assistance and 0.2 % of the variance in subjective hazard perception was due to between-person differences.

The other hypotheses were tested with repeated-measures and mixed analyses of variance (ANOVAs), multivariate ANOVAs (MANOVAs), and McNemar tests carried out with IBM SPSS statistics software (Version 22). The McNemar test was used to test differences between two related dichotomous variables. More specifically, it tested differences between the proportion of drivers who changed their alarm classification dependent on their current manoeuvre intention. Post-hoc tests were calculated with paired and unpaired *t*-tests. The significance level was set at $\alpha = 0.05$ for all analyses.

For statistical analyses, the 5-point sematic differential scale used to measure alarm acceptance was recoded to scale points ranging from 1 to 5 (-2 = 1, -1 = 2, 0 = 3, 1 = 4, 2 = 5).

It was necessary to exclude subjective as well as driving data of 11 test events with low system risk assessment (of 11 different participants) from data analysis. Inexplicably, the lead vehicle decelerated stronger than 2 m/s^2 in these events. This observation was based on subjective evaluations of the experimenter as well as on driving data. In these situations, participants decelerated more strongly and minimal TTC values were lower than in the other test events with low system risk assessment.

6.3 Results

6.3.1 Descriptives for Multilevel Analysis

For multilevel analysis, only data of the group without FCAs were considered. The initial data structure consisted of eight measurement points nested within 32 participants, $n = 249$ measurement points remained for data analysis. Figure 6-3 displays means and 95 % confidence intervals for the dependent variables subjective hazard perception and perceived need for assistance grouped by traffic scenario, system risk assessment, and manoeuvre intention.

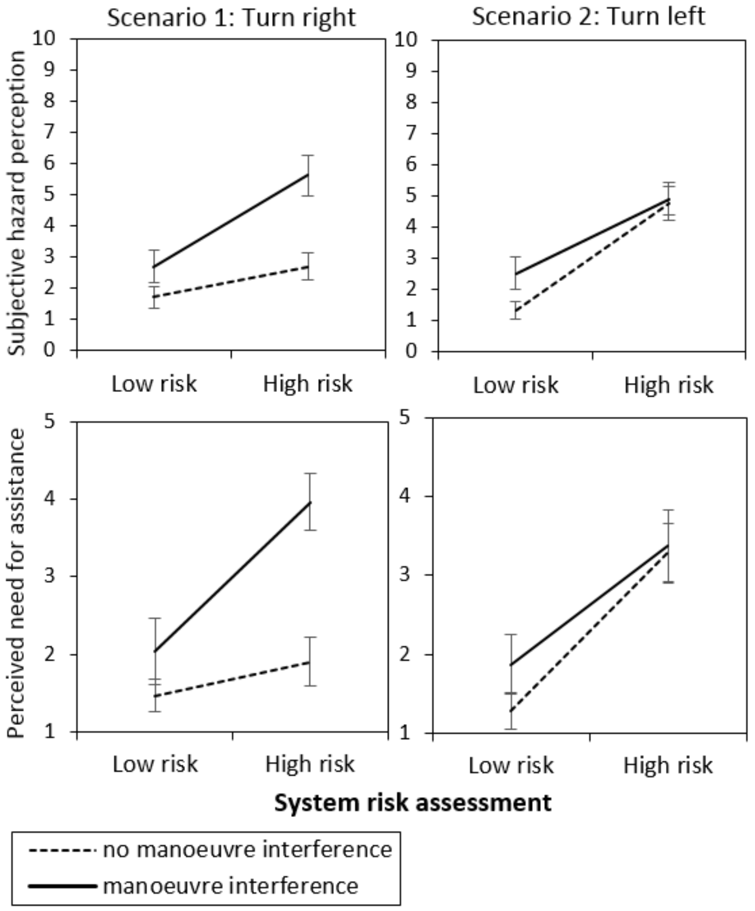

Figure 6-3. Means of subjective hazard perception (upper part) and perceived need for assistance (lower part) grouped by traffic scenario, system risk assessment, and manoeuvre intention. Error bars display 95 % confidence intervals.

There was a significant positive correlation between the variables subjective hazard perception and need for assistance, *r* (247) = .87, *p* < .001. The initial intent was to conduct the multilevel analysis including measurement points of both traffic scenarios. However, the descriptive data showed that participants' subjective evaluations of events at high system risk assessment without manoeuvre interference differed between Scenario 1 and 2 (Figure 6-3). A repeated-measures MANOVA with manoeuvre intention and traffic scenario as factors and subjective hazard perception and need for assistance as dependent variables served to test the statistical relevance of this difference. The analysis considered only measurement points with high system risk assessment and revealed a significant multivariate main effect of traffic scenario, Wilks' λ = .62, *F*(2, 30) = 9.02, *p* = .001, η_p^2 = .38, and a significant interaction of traffic scenario and manoeuvre intention, Wilks' λ = .47, *F*(2, 30) = 16.68, *p* < .001, η_p^2 = .53.

Post-hoc tests with Bonferroni adjustment showed differences between ratings for Scenario 1 and 2 when the event did not interfere with the manoeuvre intention, for subjective hazard perception ($p < .001$) as well as for need for assistance ($p < .001$).

Due to these differences, it was more appropriate to test Hypothesis 1 by carrying out two separate multilevel analyses for each traffic scenario. For each scenario, the data structure consisted of four measurement points nested within 32 participants, $n = 122$ measurement points for Scenario 1 and $n = 127$ measurement points for Scenario 2. However, to test the moderated mediation as suggested by the second hypothesis, it would have been necessary to split these two data sets each into two subgroups (see Section 5.2.7, Wegener & Fabrigar, 2000). The resulting data sets would have consisted of only two measurement points (low and high system risk assessment) nested within 32 participants with about 60 measurement points each. Under these conditions, it was not appropriate to calculate the moderated mediation analysis as initially planned. Therefore, it was only possible to conduct a multilevel analysis separately for each traffic scenario that checked if the interaction between system risk assessment and manoeuvre intention significantly predicted subjective hazard perception.

6.3.2 Mediation Analyses

To test the mediation hypothesis, the mediation analysis was conducted separately for Scenario 1 and 2 (see explanation in Section 6.3.1). With regard to Scenario 1, results showed a significant direct effect of system risk assessment on perceived need for assistance (path c in Figure 6-1), $B = 1.16$, $SE = 0.21$, $p < .001$. All parts of the mediation model were tested simultaneously (Bauer et al., 2006). System risk assessment significantly predicted subjective hazard perception (path a in Figure 6-1), $B = 1.89$, $SE = 0.24$, $p < .001$. There was a significant positive relationship between subjective hazard perception and perceived need for assistance (path b in Figure 6-1), $B = 0.56$, $SE = 0.07$, $p < .001$. When including the mediator subjective hazard perception into the model, the direct effect between system risk assessment and perceived need for assistance (path c’ in Figure 6-1) became non-significant, $B = 0.13$, $SE = 0.26$, $p = .624$. The random indirect effect via subjective hazard perception was significant, $B = 1.03$, $SE = 0.20$, $Z = 5.29$, $p < .001$. This result indicated complete mediation. With regard to Scenario 2, the direct effect of system risk assessment on perceived need for assistance (path c) was significant, $B = 1.74$, $SE = 0.21$, $p < .001$. There was a significant positive relationship between system risk assessment and subjective hazard perception (path a), $B = 2.93$, $SE = 0.27$, $p < .001$, and between subjective hazard perception and perceived need for assistance (path b), *B* = 0.48, *SE* = 0.07, *p* < .001. The direct effect between system risk assessment and perceived need for assistance became non-significant when taking subjective hazard perception into account (path c'), *B* = 0.43, *SE* = 0.25, *p* = .096. The analysis revealed a significant random indirect effect via subjective hazard perception, *B* = 1.26, *SE* = 0.18, *Z* = 7.11, *p* < .001. The first hypothesis was, therefore, supported for both traffic scenarios. Direct, indirect and total effects are displayed separately for both scenarios in Table 6-2.

Table 6-2

Multilevel Regression Analysis for Hypotheses 1 and 2

	Scenario 1: Turn right			**Scenario 2: Turn left**		
Model with mediator	***B***	***SE***	**95% CI**	***B***	***SE***	**95% CI**
Direct effect	0.13	0.26	[-0.38, 0.64]	0.43	0.25	[-0.06, 0.92]
Indirect effect	1.03***	0.20	[0.65, 1.42]	1.26***	0.18	[0.91, 1.61]
Total effect	1.16***	0.21	[0.75, 1.57]	1.74***	0.21	[1.33, 2.16]

Note. *N* = 32 participants at Level 2, measurement points at Level 1 for Scenario 1: *n* = 122, for Scenario 2: n = 127. Predictor is system risk assessment, mediator is subjective hazard perception, criterion is perceived need for assistance, and moderator is manoeuvre intention. CI = Confidence Interval [lower limit, upper limit].
†*p* < .10. **p* < .05. ***p* < .01. ****p* < .001.

6.3.3 Moderated Mediation Analyses

As described in Section 6.3.1, the moderated mediation analyses could not be conducted as initially planned. Due to the required separate analyses for both traffic scenarios, the data sets divided into the two levels of manoeuvre intention consisted of too few remaining measurement points. To gain insights into the effect of manoeuvre intention anyway, the predictive effect of the interaction between system risk assessment and manoeuvre intention on subjective hazard perception was tested separately for both traffic scenarios. When manoeuvre intention as a moderator was added to path a of the mediation model for Scenario 1, the interaction term for system risk assessment with manoeuvre intention significantly predicted subjective hazard perception, *B* = 2.09, *SE* = 0.44, *p* < .001. As demonstrated in the upper left panel of Figure 6-3, the positive relationship between system risk assessment and subjective hazard perception was stronger when the intended driving manoeuvre interfered with the braking lead vehicle. This result is in line with the second hypothesis. In contrast, with regard to Scenario 2, results revealed that the interaction term between system risk assessment and manoeuvre intention was negatively associated with subjective hazard perception, *B* = -1.12, *SE* = 0.43, *p* = .010. As demonstrated in the upper right panel of Figure 6-3, the positive relationship between system risk assessment and subjective hazard perception was stronger when the intended driving manoeuvre did *not* interfere with the braking lead vehicle. For events with high system risk assessment, manoeuvre intention had no impact on drivers' subjective hazard perception. This finding contradicts the second hypothesis.

6.3.4 Alarm Acceptance

To test the hypothesis that drivers indicate a higher acceptance for alarms issued while the hard braking lead vehicle interferes with their current manoeuvre intention than without interference, only data of the group with FCAs and situations with high system risk assessment (TTC < 1.9 seconds) were considered.

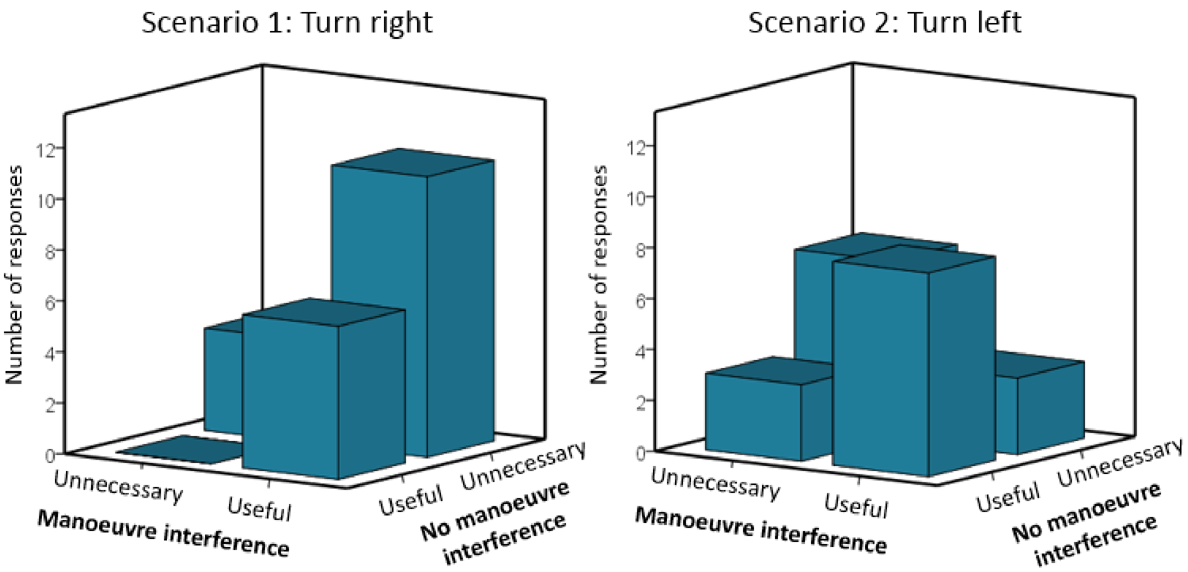

Figure 6-4. Proportion of alarm classification as unnecessary or useful dependent on manoeuvre intention in Scenario 1 (left) and Scenario 2 (right).

To ensure that the predefined classification of alarms as useful during events with manoeuvre interference and as unnecessary during events without manoeuvre interference matched drivers' subjective classifications, McNemar tests analysed the impact of manoeuvre intention on drivers' subjective alarm classification. For Scenario 1, the results showed that alarm classification significantly changed with manoeuvre intention, *p* = .001. As illustrated by the left panel of Figure 6-4, the proportion of drivers who perceived FCAs as unnecessary significantly increased from events with manoeuvre interference to events without manoeuvre interference. For Scenario 2, there was no significant difference between the proportions of drivers who perceived alarms as useful or unnecessary with different manoeuvre intentions, *p* = 1.

The proportion of alarm classification for Scenario 2 is displayed in the right panel of Figure 6-4. Thus, the predefined alarm classification matched drivers' subjective alarm classification in Scenario 1, while there was a mismatch for Scenario 2. Anyway, alarm acceptance was analysed for both scenarios. To consider potential differences in alarm acceptance between the two traffic scenarios, traffic scenario was included as factor in the analysis carried out to test Hypothesis 3. A repeated-measures ANOVA tested the impact of manoeuvre intention and traffic scenario on alarm acceptance. The corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014) are displayed in Figure 6-5. There was a significant interaction between manoeuvre intention and traffic scenario, $F(1, 20) = 18.79$, $p < .001$, $\eta_p^2 = .48$. In Scenario 1, a paired *t*-test showed that drivers' acceptance was higher for alarms activated while the lead vehicle interfered with their current manoeuvre intention than without interference, $t(20) = 5.93$, $p < .001$, $d_{Cohen} = 1.29$. In contrast, manoeuvre intention had no impact on alarm acceptance in Scenario 2, $t(20) = 0.26$, $p = .796$, $d_{Cohen} = 0.06$. The results of Scenario 1 were in line with the third hypothesis, while those of Scenario 2 did not support it.

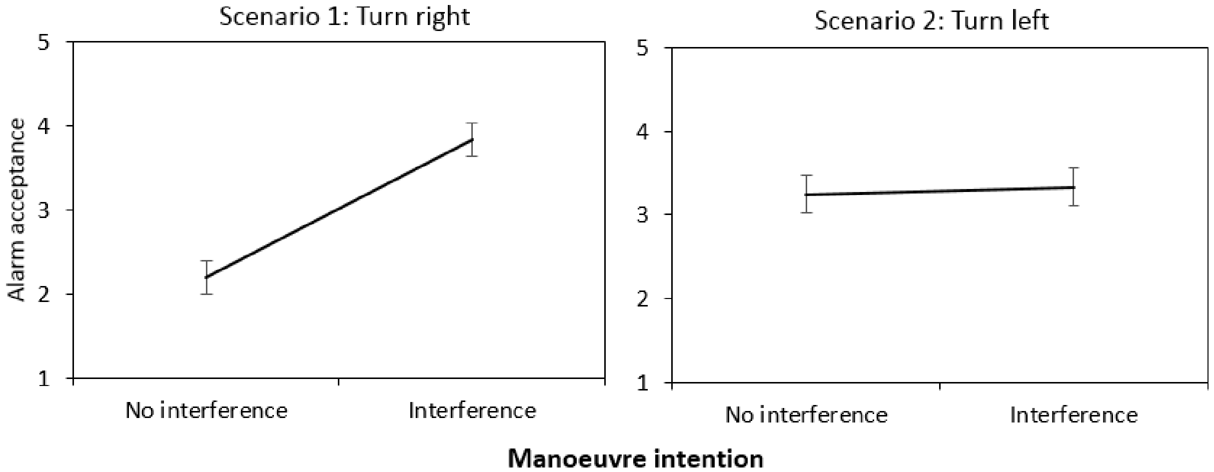

Figure 6-5. Acceptance of alarms activated with and without interference with drivers' manoeuvre intention during Scenario 1 (left) and Scenario 2 (right). Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

As the analysis of drivers' subjective alarm classification revealed that manoeuvre intention did not always determine their classification of alarms as either useful or unnecessary (especially in Scenario 2), an additional analysis was conducted to gain insights into drivers' acceptance of unnecessary alarms. For each event in which drivers received an FCA, an unpaired *t*-test tested the effect of drivers' subjective alarm classification on their alarm acceptance.

Subjective alarm classification was used as between-subject factor with two levels (useful, unnecessary). Figure 6-6 shows the corresponding group sizes, means and 95 % confidence intervals. According to Levene's test for equality of variances, variances were equal for each *t*-test even though the groups were of unequal size (Figure 6-6). All *t*-tests showed that alarms subjectively classified as useful were significantly more accepted than alarms classified as unnecessary. The test statistics are reported in Table 6-3.

Table 6-3

Results of t-tests that Tested the Effect of Subjective Alarm Classification on Alarm Acceptance

Alarm activated in:	***t***	***df***	d_{Cohen}
Scenario 1: Turn right			
No manoeuvre interference	-7.90***	19	3.84
Manoeuvre interference	-4.85***	19	2.70
Scenario 2: Turn left			
No manoeuvre interference	-4.98***	19	2.16
Manoeuvre interference	-5.68***	19	2.49

Note. *p < .05. **p < .01. ***p < .001.

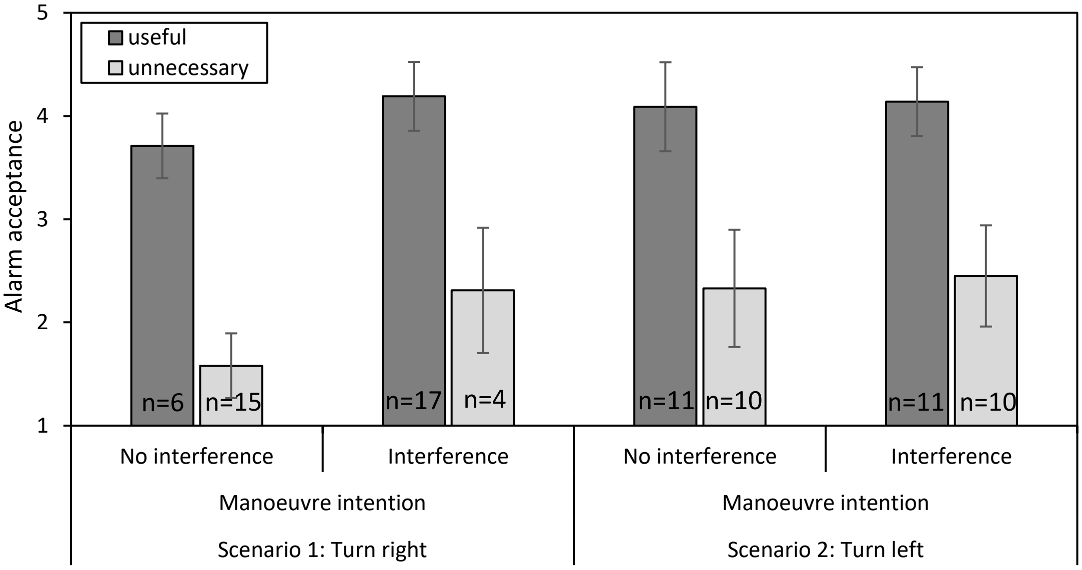

Figure 6-6. Means of alarm acceptance grouped by traffic scenario, manoeuvre intention, and subjective alarm classification. Error bars display 95 % confidence intervals.

6.3.5 Driver Responses to Unnecessary Alarms

The analyses of driver behaviour only considered data of situations with high system risk assessment (TTC < 1.9 seconds) and without manoeuvre interference in which the potential conflict dissolved. Drivers' responses to unnecessary alarms were compared to behaviour of drivers who experienced the same situation without FCA. To consider potential differences in driver behaviour between the two traffic scenarios, traffic scenario was included as a factor in the analysis. A mixed MANOVA tested the impact of traffic scenario and level of assistance on drivers' magnitude of speed reduction and maximum deceleration. Table 6-4 reports the test statistics of the multivariate and univariate tests. Figure 6-7 illustrates the corresponding means and 95 % confidence intervals. Even though not further considered in the statistical analyses, Figure 6-7 additionally shows the means and 95 % confidence intervals for the condition when drivers' manoeuvre intention interfered with the traffic event and the conflict remained.

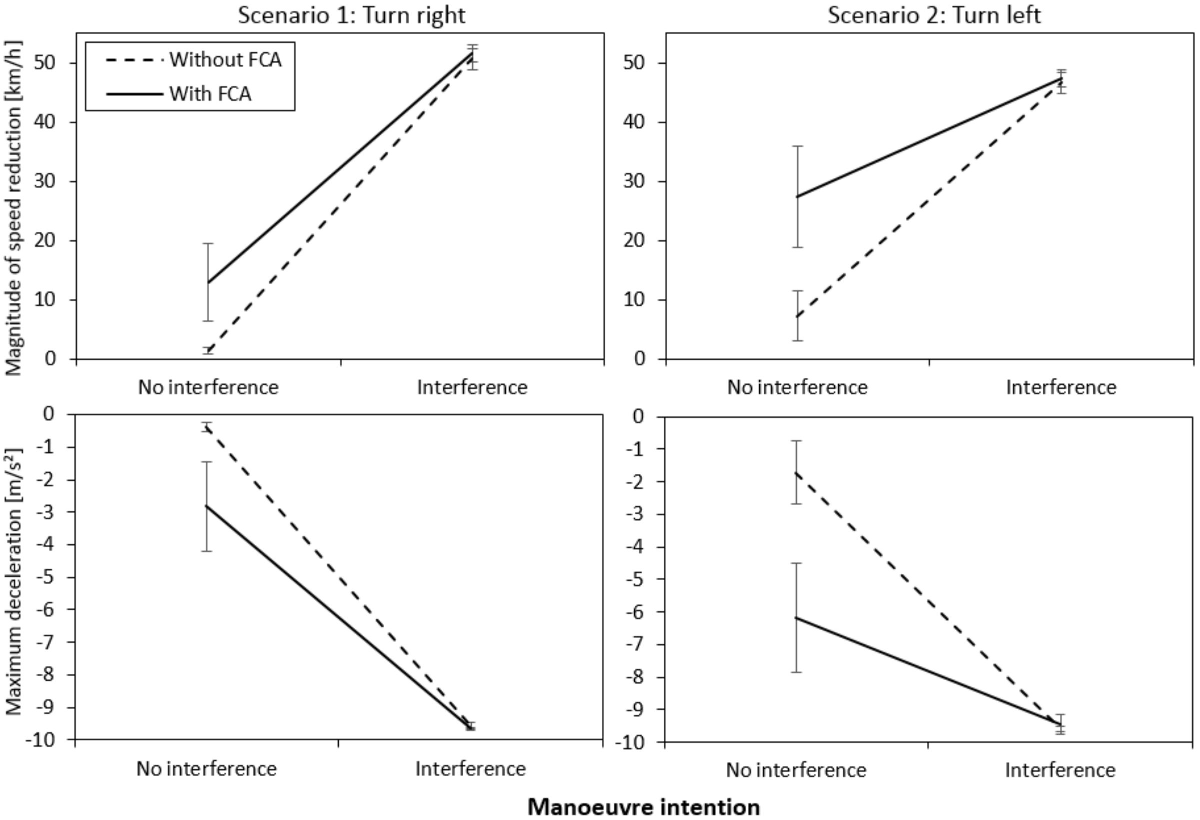

Figure 6-7. Means of magnitude of speed reduction (upper part) and maximum deceleration (lower part) grouped by traffic scenario, manoeuvre intention, and level of assistance. Error bars display 95 % confidence intervals.

The MANOVA revealed significant multivariate and univariate main effects of level of assistance. When drivers' manoeuvre intention resulted in a dissolving outcome of the conflict (no manoeuvre interference), drivers reduced their speed to a higher extent and decelerated more strongly with FCA than without FCA. Moreover, there were significant multivariate and univariate main effects of the factor scenario. Overall, drivers' magnitude of speed reduction and maximum deceleration were more intense in Scenario 2 than in Scenario 1. Significant multivariate and (marginally) significant univariate interactions between scenario and level of assistance showed that especially when receiving unnecessary alarms, drivers reduced their speed to a higher extent and decelerated more strongly in Scenario 2 than in Scenario 1.

Table 6-4

Results of MANOVA with Multivariate and Univariate Effects of Traffic Scenario and Level of Assistance on Magnitude of Speed Reduction and Maximum Deceleration

	df1	***df2***	**Wilks' λ**	***F***	**η_p^2**
Multivariate effects					
Scenario	2	50	.66	12.91***	.34
Level of assistance	2	50	.61	15.93***	.39
Scenario*Level of Assistance	2	50	.91	2.43†	.09
Univariate effects					
Magnitude of speed reduction					
Scenario	1	51		18.58***	.27
Level of assistance	1	51		31.36***	.38
Scenario*Level of Assistance	1	51		3.42†	.06
Maximum deceleration					
Scenario	1	51		25.58***	.33
Level of assistance	1	51		32.01***	.39
Scenario*Level of Assistance	1	51		4.77*	.09

Note. Without FCA: $n = 32$; with FCA: $n = 21$.
†$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

6.4 Discussion

The second study sought to provide evidence for several research questions. First, the study aimed to extend the findings of Study 1 by addressing the same research questions with methodological modifications (Figure 5-1). Second, the impact of unnecessary alarms on drivers' alarm acceptance was examined. Third, the study investigated how drivers respond to unnecessary alarms. Therefore, 53 participants encountered two different traffic scenarios with a braking lead vehicle that would either result in low or high system risk assessment. Each scenario was experienced with two different manoeuvre intentions to vary the anticipated outcome of the potential conflict. One group of drivers received an FCA during events with high system risk assessment and the other group experienced the same events without FCA.

Similar to Study 1, the results were in line with the mediation hypothesis. The *retrospective* subjective hazard perception mediated the positive relationship between system risk assessment and drivers' perceived need for assistance in both traffic scenarios. Due to different subjective evaluations of the two traffic scenarios with high system risk assessment, the analyses were carried out separately for the two traffic scenarios. Similar to the findings of Study 1, drivers' (retrospective) subjective hazard perception was the central factor that influenced their perceived need for assistance in both scenarios, instead of system risk assessment that is exclusively determined by a prediction based on physical criteria (TTC). As proposed by the theoretical framework of drivers' subjective alarm evaluation, drivers' perceived need for assistance was predicted by their *retrospective* subjective hazard perception (Number 1 in Figure 5-1).

To examine the research question if an advantage of the driver over the system on the anticipation level (Number 3 in Figure 5-1) causes a discrepancy between system risk assessment and drivers' retrospective subjective hazard perception (Number 2 in Figure 5-1), drivers encountered identical traffic events with different manoeuvre intentions. The findings of this study did not provide clear answers to these research questions. As the number of remaining measurement points in the subgroup data sets of each traffic scenario did not allow to carry out the moderated mediation analysis as initially planned, the reported findings are based on the predictive value of the interaction between system risk assessment and manoeuvre intention on retrospective subjective hazard perception. In Scenario 1, drivers perceived events with high system risk assessment as more hazardous in retrospect when their manoeuvre intention caused a remaining conflict than a dissolving outcome of the conflict with the lead vehicle. In contrast, in Scenario 2, drivers' retrospective subjective hazard perception of events with high system risk assessment did not differ dependent on their current manoeuvre intention. While the findings of Scenario 1 supported the assumptions based on the theoretical framework (Number 2 and 3 in Figure 5-1), the results of Scenario 2 did not provide evidence for them. The intent to use two different traffic scenarios was to increase the number of measurement points for statistical analyses. There were no expectations concerning differences between the scenarios. To find possible explanations for these deviating results, different driving parameters were compared between the traffic scenarios with regard to the events with high system risk assessment and without manoeuvre interference. Drivers' speed when the lead vehicle started to decelerate was higher in Scenario 1 than in Scenario 2,

$t(52) = 2.76$, $p = .008$, $d_{Cohen} = 0.38$. The minimal TTC between ego and lead vehicle was lower in Scenario 1 than in Scenario 2, $t(52) = 6.79$, $p < .001$, $d_{Cohen} = 0.93$. The maximum steering angles to the left and to the right were higher in Scenario 2 than in Scenario 1, right $t(52) = 5.94$, $p < .001$, $d_{Cohen} = 0.82$, and left $t(52) = -9.81$, $p < .001$, $d_{Cohen} = 1.35$. It seems counterintuitive that drivers perceived Scenario 2 as more hazardous even though their initial speed was higher and the minimal TCC was lower in Scenario 1. However, the maximum steering angles in both directions were larger in Scenario 2 which might indicate an interim perceived loss of control. Another explanation might be a different subjective impression of spatial separation to the lead vehicle. In Scenario 1, drivers were never at risk to collide with the lead vehicle due to the barrier surface next to the lead vehicle (Figure 6-2). In Scenario 2, drivers would have been at risk to collide with the lead vehicle if they had not turned onto the left turning lane directly at its beginning. This might have increased drivers' retrospective subjective hazard perception. A general limitation of the used traffic scenarios could be that the situations with high system risk assessment that dissolved due to drivers' manoeuvre intention were forced by the behaviour of the lead vehicle. The lead vehicles provoked the low TTC values by a sudden deceleration without obvious reason. Thus, drivers' advantage over the system in anticipating a dissolving outcome of a conflict became relevant just a maximum of two seconds before a potential crash could have happened. It is assumed that a combination of this methodological limitation and the lack of perceived spatial separation could be the most probable explanation for the deviating results of Scenario 2.

In general, manoeuvre intention could have a greater impact on subjective hazard perception if drivers themselves provoke low TTC values, e.g. by approaching a parked or stopped lead vehicle as a prelude to turn. In experimental studies, it is difficult to manipulate such a behaviour as most participants drive cautiously and rule-compliantly when taking part in a driving simulator study. Moreover, in the simulator training in which each participant had taken part, drivers were explicitly trained to drive safely (Hoffmann et al., 2003).

Drivers' alarm acceptance also differed between the two traffic scenarios. The results for Scenario 1 supported the third hypothesis. Drivers indicated a higher acceptance for FCAs issued while the lead vehicle interfered with their current manoeuvre intention and the conflict remained than for FCAs activated without interference where the potential conflict dissolved. Drivers' subjective classification of alarms as useful and unnecessary basically matched the predefined classification according to manoeuvre intention. In Scenario 2, however, there was a mismatch between drivers' subjective alarm classification and the predefined alarm classification. When the lead vehicle did not interfere with drivers' manoeuvre intention, half of the drivers perceived FCAs as useful and the other half as unnecessary. This was also the case during situations in which their intention interfered with the braking lead vehicle. Accordingly, the acceptance ratings did not differ between events with and without manoeuvre interference. Anyway, the study provided insights into drivers' acceptance of unnecessary alarms. Alarms classified as unnecessary by drivers themselves were less accepted than alarms classified as useful. This finding extends prior research on acceptance of unnecessary alarms (e.g. Cotté et al., 2001; Naujoks et al., 2016; Zarife, 2014).

Moreover, the study investigated short-term effects of unnecessary alarms on driver responses. Therefore, driving behaviour in response to unnecessary FCAs was compared to natural driving behaviour in the same situations without FCAs. Alarms were considered as unnecessary when the inter-vehicle conflict dissolved as the ego driver intended to turn directly behind the braking lead vehicle (no manoeuvre interference). Results showed that drivers who received unnecessary FCAs reduced their speed to a higher extent and decelerated more strongly than drivers who experienced the same situation without FCAs. This difference was greater in Scenario 2 than in Scenario 1. Drivers who did not receive unnecessary alarms in situations without manoeuvre interference mostly reacted with only minimal speed reductions and decelerations. This finding indicated that the anticipation of a dissolving outcome was principally possible. However, this ability did not lead to responses of similar low intensity to unnecessary alarms. Especially in Scenario 2, unnecessary alarms caused drivers to respond with moderate braking. The findings are in line with the study by Lees and Lee (2007) in which unnecessary alarms caused unnecessary braking responses. Additionally, the results supported the assumption that the process of cross-checking the validity of an unnecessary alarm might be very demanding without prior experience with situations usually associated with unnecessary alarms (Gérard & Manzey, 2010). With increasing system and alarm experience, drivers might develop an understanding of traffic constellations that typically activate unnecessary alarms. This knowledge might simplify the process of validating an unnecessary alarm and to select a less intense alarm response. Therefore, drivers' responsiveness to unnecessary alarms is expected to decrease with increasing system experience as shown in the naturalistic driving studies by Flannagan et al. (2016) and General Motors Corporation (2005). Study 4 will investigate the impact of a repeated exposition to unnecessary alarms in similar traffic constellations on drivers' alarm responses.

6.5 Conclusion

Study 2 provided further evidence for assumptions derived from the theoretical framework of drivers' subjective alarm evaluation. Similar to Study 1, it has been found that drivers' subjective hazard perception of an encountered traffic event mediated the relationship between system risk assessment and their perceived need for assistance. As a methodological modification to Study 1, drivers evaluated their subjective hazard perception *after* they had already encountered the traffic event. In line with Hypothesis I of the theoretical framework (Number 1 in Figure 5-1), drivers' retrospective subjective hazard perception determined their perceived need for assistance. The assumption that an advantage of drivers over the system on the anticipation level by considering their current manoeuvre intention (Number 3 in Figure 5-1) would result in a discrepancy between system risk assessment and drivers' retrospective subjective hazard perception (Number 2 in Figure 5-1) was only supported by Scenario 1. In Scenario 2, drivers' subjective hazard perception was not influenced by their manoeuvre intention to either stay or turn behind the lead vehicle. The reasons for these different results are unclear. The most probable explanation was a different subjective impression of spatial separation to the lead vehicle. Moreover, it is assumed that manoeuvre intention might have a greater potential to lead to discrepancies between the system's and the driver's anticipation and, thus, between system risk assessment and subjective hazard perception when the driver himself provokes low TTC values, e.g. by approaching a parked or stopped lead vehicle as a prelude to turn.

The study provided insights into drivers' acceptance of unnecessary alarms. The results revealed that drivers evaluate alarms which they themselves have classified as unnecessary as less acceptable than alarms which they have classified as useful. However, their subjective classification of alarms as useful or unnecessary did not always match the predefined classification based on their current manoeuvre intention.

The findings of Study 2 showed that drivers who received unnecessary alarms reduced their speed to a higher extent and decelerated more strongly than drivers who showed their natural driving behaviour in the same situations without receiving alarms. With short-term system experience, unnecessary alarms led to braking responses of moderate intensity.

7 Study 3: Intentions Attributed to Other Road Users[3]

7.1 Introduction and Research Questions

The third study aimed to provide evidence for a further factor that may cause an advantage of human anticipation over the system's prediction and, thus, discrepancies in human hazard perception and system risk assessment with regard to the same event in the environment. This factor was the human ability to infer intentions of other road users from cues in the environment in which their actions are embedded. Furthermore, the study sought to gain deeper insights into reasons for varying degrees of acceptance of unnecessary alarms and examined short-term effects of unnecessary alarms on driver responses. The study addressed the following research questions (see Section 3.2).

- Does a discrepancy between system risk assessment and drivers' subjective hazard perception result from advantages of the driver over the system in anticipating a dissolving outcome of a potential conflict based on the consideration of intentions attributed to other road users?
- Which factors influence drivers' acceptance of unnecessary alarms?
- How do drivers respond to unnecessary alarms?

Data of naturalistic driving studies by General Motors Corporation (2005) and Flannagan et al. (2016) showed that in 16 to 32 % of all activated FCAs the lead vehicle turned out of the ego vehicle's lane after FCA activation (see Sections 2.3.2 and 2.3.4). In these situations, alarms were activated by TTC values that fell below the activation threshold while the potential inter-vehicle conflict finally dissolved due to lead vehicle behaviour. These data demonstrate that conventional FCA systems have difficulties to analyse the meaning of multiple and complex environmental cues to achieve a complete comprehension of the situation. The system's prediction of other road users' behaviour in the near future is determined by physical measurements concerning the ego vehicle and the potential conflict partner. Based on the theoretical considerations of this thesis, it is assumed that participants of the naturalistic driving studies were able to comprehend the meaning of specific cues in the environment, such as an intersection in combination with a stopped lead vehicle, activated turn indicator of the lead vehicle, green traffic lights, a crosswalk in the turning street, and a pedestrian who has almost crossed

---

[3] Parts of Chapter 7 have been published in Kaß, Schmidt, and Kunde (2018b) and Kaß et al. (2019).

this crosswalk. This comprehension presumably served as a basis to infer the intention of the other driver and to anticipate his or her subsequent actions (see Sections 2.1.2.4 and 3.1). Drivers might have not responded or only responded minimally to the FCAs because they anticipated a dissolving outcome of the potential conflict. As drivers in other vehicles are often not directly observable, ego drivers might have considered the other vehicles' actions and movements, and the context with environmental cues for the anticipation of other vehicles' subsequent movements (Simon & Bullinger, 2018; Stahl et al., 2014). It is hypothesised that, in some traffic situations, drivers have an advantage over the system in anticipating subsequent actions of other road users which result in a dissolving outcome of a potential conflict. When drivers are able to anticipate that the lead vehicle will leave the lane in the near future, while the TTC between ego and lead vehicle falls below a predefined critical threshold, system risk assessment is assumed to exceed human retrospective subjective hazard perception. Drivers might perceive such a situation as little hazardous and have a low perceived need for assistance (see Sections 3.1, 5.5, and 6.5). As a consequence, drivers are assumed to perceive activated FCAs as unnecessary.

Under natural driving conditions when not being warned, drivers would conceivably not or only minimally reduce their speed in a situation as described in the previous paragraph. They know that a speed reduction is not necessary as the other vehicle will no longer constitute a crash threat in the course of time and the conflict will finally dissolve. With regard to drivers' responses to unnecessary alarms, Study 2 showed that drivers who do not have much prior alarm experience responded to unnecessary alarms with moderate braking responses even if they were able to anticipate a dissolving outcome of the conflict. Accordingly, in the present study, it is also assumed that drivers who receive unnecessary alarms respond more intensively than drivers who do not receive an alarm in the same situation with a predictable dissolving outcome. Furthermore, drivers are assumed to indicate little acceptance for unnecessary alarms when they were already able to anticipate that the behaviour of another road user will result in a dissolving conflict.

In contrast, unnecessary alarms can also be caused by another road user whose intentions and subsequent actions were neither predictable for the system nor for the driver. In such a situation, both system and driver have initially classified the behaviour of the other road user as potentially hazardous. In the course of the driving situation, the behaviour of the potential conflict partner turns out to be non-hazardous. Figure 2-6 illustrates an example of such an unpredictable and unnecessary alarm scenario (Zarife, 2014). A cyclist is approaching the road from the side and finally turns and drives along the sidewalk before it could have crossed the driver's way. When unnecessary alarms are activated in situations with unpredictable behaviour of other road users, previous studies revealed that these alarms resulted in unnecessary braking reactions and did not decrease perceived ease of use, usefulness, and trust in comparison to a perfectly reliable system (Lees & Lee, 2007; Naujoks et al., 2016). When not being able to predict the subsequent actions of other road users that result in a dissolving outcome of the conflict, drivers might perceive the situation as more hazardous in retrospect and indicate a higher need for assistance. Even without receiving an FCA, drivers might reduce their speed to a certain extent as a precaution when they cannot anticipate the other road user's subsequent actions. Therefore, the difference between driver behaviour with and without unnecessary alarm is assumed to be lower than in situations with predictable lead vehicle behaviour. Furthermore, drivers might indicate more acceptance for unnecessary alarms when not having an advantage over the system in anticipating the behaviour of other road users. Given a situation with a braking lead vehicle that causes TTC values that fall below a predefined critical threshold and, thus, result in a high system risk assessment, the following hypotheses were formulated.

Hypothesis 1. If a potential inter-vehicle conflict dissolves due to the subsequent action of the braking lead vehicle …

- **a.** … drivers perceive the situation as less hazardous in retrospect when they were able to anticipate the behaviour of the lead vehicle than if not.
- **b.** … drivers perceive a lower need for assistance when they were able to anticipate the behaviour of the lead vehicle than if not.

Hypothesis 2. If a potential inter-vehicle conflict dissolves due to the subsequent action of the braking lead vehicle, drivers evaluate FCAs as less acceptable when they were able to anticipate the behaviour of the lead vehicle than if not.

Hypothesis 3. If a potential inter-vehicle conflict dissolves due to the subsequent action of the braking lead vehicle …

- **a.** … drivers reduce their speed to a lower extent and decelerate less strongly under natural driving conditions when they were able to anticipate the behaviour of the lead vehicle than if not.
- **b.** … drivers who receive an unnecessary alarm reduce their speed to a higher extent and decelerate more strongly than drivers who do not receive an alarm. This difference is more pronounced when drivers were able to anticipate the behaviour of the lead vehicle than if not.

7.2 Method

7.2.1 Participants

A total of 43 experienced drivers (22 female, 21 male) took part in the study. Data of two participants were excluded because they drove too slowly in at least five out of twelve test events resulting in TTC values that exceeded two seconds (= threshold for receiving FCAs). Consequently, data of 41 participants (20 female, 21 male) were considered for data analysis. They were between 28 and 62 years old (*M* = 42.90 years, *SD* = 10.81). Previous studies revealed that experienced drivers outperform novice drivers in hazard detection, prediction, and in adequately responding to hazards (Crundall, 2016; Lee et al., 2008; Smith, Horswill, Chambers, & Wetton, 2009; Wallis & Horswill, 2007). Therefore, only experienced drivers took part in the study. To be classified as experienced (Wallis & Horswill, 2007), drivers have held their drivers' license for 10 years or more (*M* = 23.88, *SD* = 9.88, Min = 10) and covered more than 8,000 km per year (*M* = 20,780, *SD* = 14,303, Min = 8,000). On average, they had medium prior experience with FCA systems, *M* = 3.41, *SD* = 1.58 on a 5-point Likert scale (1 = *very little*, 2 = *little*, 3 = *medium*, 4 = *much*, 5 = *very much experience*). However, the majority of participants (*n* = 28) indicated to have gained this experience during prior driving studies and only five drivers from driving in their own car. Participants were recruited from the WIVW driver test panel. Each of them had received at least four hours simulator training in two training sessions (Hoffmann et al., 2003). The rationale behind this training is explained in Section 5.2.1.

7.2.2 Apparatus

The study was conducted in the driving simulator at WIVW GmbH (see Section 4.1).

7.2.3 Experimental Design

The experiment used a 2x2x2 mixed design with lead vehicle behaviour and predictability as within-subject factors and level of assistance as between-subject factor (Table 7-1). The initial situation was the same for each test event. Participants followed the lead vehicle at 50 km/h. Just before an intersection, the lead vehicle activated its turn indicator for 400 milliseconds before it suddenly braked to a standstill. Due to this event, TTC values between ego and lead vehicle always fell below two seconds (minimal TTC values: *M* = 1.27 seconds, *SD* = 0.46). The braking lead vehicle either stayed in the same lane as the ego driver for 4 seconds (a) or turned and left the lane (b). In the latter case, the lead vehicle remained stopped for only 150 milliseconds before it started again and turned at the intersection. Participants could have driven on at a constant speed of 50 km/h without causing a collision. Therefore, the potential conflict dissolved and alarms in these situations were considered as unnecessary. Thus, only half of the situations could effectively lead to a collision as the conflict with the lead vehicle remained. The factor lead vehicle behaviour was included in the experiment to achieve different outcomes of potential inter-vehicle conflicts and to prevent learning effects. Thus, there was a balanced probability for the subsequent action of the lead vehicle. Predictability was manipulated by the context in which the lead vehicle’s action of signalling and braking was embedded. Environmental cues that are indicative for the subsequent action of the lead vehicle were either present or occluded. Thus, drivers could either predict (a) or not predict (b) subsequent lead vehicle behaviour. The realisation of the traffic scenarios is described in Section 7.2.4. The factor level of assistance was represented by either receiving an FCA during each test event with a TTC value that fell below two seconds (a) or never receiving an FCA (b) (except for one FCA during the practice drive, see Section 7.2.6). FCAs were considered as unnecessary when the braking lead vehicle left the lane to turn and the potential conflict dissolved. The used type of FCA is described in Section 4.2. To obtain groups of approximately equal size, subjects were quasi randomly allocated to the two groups (with FCAs *n* = 22; without FCAs *n* = 19). This means that the number of participants randomly assigned to each level of assistance was limited.

Table 7-1

Experimental Design of Study 3 with Group Sizes

		Level of assistance[b]	
		Without FCA	With FCA
Lead vehicle behaviour[a]	**Predictability**[a]	*n*	*n*
Lead vehicle stays in the lane	Predictable	19	22
	Unpredictable	19	22
Lead vehicle leaves the lane	Predictable	19	22
	Unpredictable	19	22

Note. [a] Within-subject factor. [b] Between-subject factor.

To reduce carry-over from one event to another and to increase the number of measurement points, participants experienced all factor combinations with three different traffic scenarios. Additionally, the study included four filler events of each of the three traffic scenarios (4 x 3 = 12 filler events). Section 7.2.4 describes the realisation of the test and filler events. Thus, all participants encountered 12 test events and 12 filler events throughout the experiment. To control for transition effects, the sequence of the 12 test events was permutated to four different sequences. The filler events were randomly allocated between the test events. Subjects were quasi randomly distributed to the four sequences with cell sizes of *n* = 8 — 12 drivers. To obtain groups of approximately equal size, the number of participants randomly assigned to each sequence was limited.

7.2.4 Traffic Scenarios

The driving environment consisted of an urban environment with a speed limit of 50 km/h and evenly distributed traffic. To attain equal velocity conditions between different participants and traffic scenarios, drivers used a speed limiter with a maximum velocity of 50 km/h. Participants drove through streets with regular turning-off streets, parked vehicles at the roadside, and pedestrians at the sidewalk.

To ensure salience and predictive power of the environmental cues used to manipulate predictability, a pre-test with 27 participants (11 female, 16 male) was conducted using the situation awareness global assessment technique (SAGAT) method by Endsley (1995). On average, participants were *M* = 35.04 (*SD* = 8.93) years old and had a driving experience of *M* = 15.77 (*SD* = 8.65) years. They were recruited from both the WIVW and Opel participant test panels.

Participants watched videos of the scenarios. The screen was blanked at the moment the lead vehicle started to brake. Participants were asked to explain the scenario, what is going to happen next and how they would react in this situation. Based on these results, salience and predictive power of the environmental cues were revised and adjusted.

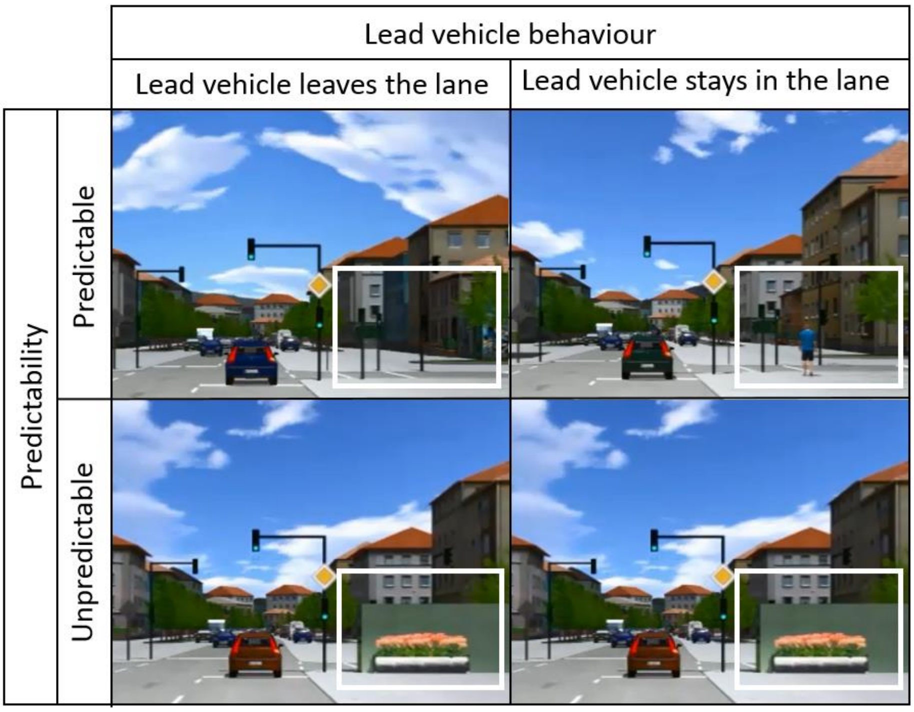

Figure 7-1. Realisation of the within-subject factors lead vehicle behaviour and predictability in Scenario 1. Environmental cues that served to predict (upper part) or not predict (lower part) lead vehicle behaviour are marked by a white frame.

Participants experienced all factor combinations with three different traffic scenarios. In the first scenario, a pedestrian on a crosswalk in the right turning street served as the cue to predict that the lead vehicle will stay in the lane as long as the pedestrian crosses the street. A free crosswalk indicated that the lead vehicle will leave the lane as it could immediately start again and turn into the right turning street at the intersection. In the unpredictable condition, the view on the crosswalk was obscured by a wall. Figure 7-1 shows the realisation of all factor combinations in Scenario 1. Based on the results of the pre-test, the pedestrian was modified in such a way that he became more salient. The second scenario was almost similar to the first one. However, the crosswalk was located in the left turning street. Additional to the pedestrian on the crosswalk, another vehicle waiting in front of the crosswalk served as a cue to predict that the lead vehicle will stay in the lane. The results of the pre-test showed that drivers often oversaw the pedestrian alone in the left turning street. In the third scenario, there was a bus station at the beginning of the right turning street with a stopped bus with activated hazard lights that blocked the street. The lead vehicle stayed in the lane when the bus remained stopped with continuously activated hazard lights. In the condition when the lead vehicle left the lane, the bus deactivated its hazard lights and started driving. In the unpredictable condition, the view on the bus was obscured by a wall. Figure 7-2 shows the realisation of events in which participants could predict that the lead vehicle would stay in the lane in Scenario 2 and 3.

Figure 7-2. Realisation of the factor combination vehicle stays in the lane and predictable lead vehicle behaviour in Scenario 2 (left) and Scenario 3 (right). Environmental cues that served to predict lead vehicle behaviour are marked by a white frame.

In the filler events, environments were similar to those in the test events. However, the turning streets were always free and the lead vehicle turned without prior deceleration at the intersection. As the minimum TTC never fell below the alarm activation threshold of two seconds in these situations, participants in the group with FCAs did not receive an alarm. The TTC values were calculated using Equation 1 in Section 4.2.

7.2.5 Dependent Measures

After each test event, all participants indicated their retrospective subjective hazard perception and perceived need for assistance. In the group with FCAs, participants additionally rated their alarm acceptance. All questions were presented and answered on a tablet (see Section 4.1).

As described in Section 4.3, the Situation Criticality Scale by Neukum et al. (2008) served to measure retrospective subjective hazard perception. For reasons of easier readability, the term “subjective hazard perception” will be used without “retrospective” throughout the results section.

Perceived need for assistance was measured by one item that was introduced by the statement “In this traffic situation, I would have liked a collision warning” in the group without FCAs and “[…], I liked to have a collision warning” in the group with FCAs. Participants answered the item on a 5-point Likert scale (1 = *disagree,* 2 = *rather disagree,* 3 = *neither agree nor disagree,* 4 = *rather agree,* 5 = *agree*).

As described in Section 4.3, alarm acceptance was measured by using the usefulness subscale of the acceptance questionnaire by van der Laan et al. (1997). Mean internal consistency was α = .94.

To assess driver responses to the test events, the magnitude of speed reduction and maximum deceleration were measured (see Section 4.3).

7.2.6 Procedure

The study was approved by the Ethics Committee of the Institute for Psychology of the Julius-Maximilians-University Würzburg. Upon arrival, participants received written instructions containing information about the purpose of the study, the simulation environment, the speed limit of 50 km/h, driving with a speed limiter, and an explanation of every single verbal category and the cut-off point of the situation criticality scale. They were informed that the study examines their behaviour in and their subjective evaluations of different traffic situations to gain insights into drivers’ need for collision alarms. Additionally, participants signed a consent form that informed them about their right to decline to participate and to withdraw from the study at any point, and the method of data anonymization.

Participants drove a five-minute practice drive that included a situation with a braking lead vehicle in which an FCA was issued to let them get a better idea about its nature and modality (see Section 4.2). Participants in the group without FCAs were instructed that they should base their ratings concerning perceived need for assistance on this kind of alarm. Throughout the experimental drive, each test scenario was followed by a programmed announcement “Please stop here” after participants have passed the intersection. This method aimed to avoid that drivers would stop at any event with a braking lead vehicle which could have influenced driving measures. After having stopped, drivers answered questions on the tablet concerning the encountered scenario. Overall, the study took about 1.5 hours per participant. At the end of the experiment, participants were thoroughly debriefed.

7.2.7 Data Analysis

The hypotheses were tested with repeated-measures and mixed ANOVAs and MANOVAs. Post-hoc tests were calculated with paired *t*-tests. All analyses were carried out using IBM SPSS statistics software (Version 22). The significance level was set at $\alpha = 0.05$. Dependent measures analysed in the statistical tests reflect averaged ratings of the three different traffic scenarios.

For statistical analyses, the 5-point semantic differential scale used to measure alarm acceptance was recoded to scale points ranging from 1 to 5 (-2 = 1, -1 = 2, 0 = 3, 1 = 4, 2 = 5).

A criterion for excluding measurement points from data analysis was a TTC value greater than two seconds due to slow driving. The rationale behind this criterion was that participants in the group with FCAs did not receive an alarm under this condition. For consistency reasons, this criterion was also adopted to the group without FCAs. In total, 15 measurement points (out of 516 measurement points in total) of 12 different participants were excluded from data analysis. As already mentioned in Section 7.2.1, complete data sets of two participants were additionally excluded as they drove too slowly in at least five out of twelve test events.

7.3 Results

7.3.1 Subjective Hazard Perception and Perceived Need for Assistance

To test the first hypothesis that drivers perceive dissolving conflicts as less hazardous and perceive a lower need for assistance when they were able to anticipate the behaviour of the lead vehicle than if not, a mixed MANOVA with lead vehicle behaviour and predictability as within-subject factors, level of assistance as between-subject factor, and subjective hazard perception and perceived need for assistance as dependent variables was carried out. Even though there were no a priori hypotheses concerning the impact of level of assistance, it was included as additional factor to consider its potential impact on drivers' subjective hazard perception and need for assistance. Table 7-2 reports the test statistics of the relevant multivariate and univariate tests. Figure 7-3 illustrates the corresponding means of subjective hazard perception and perceived need for assistance averaged over both levels of assistance and the within-group standard errors of the means (O'Brien & Cousineau, 2014).

There were significant multivariate and univariate main effects of predictability on subjective hazard perception and perceived need for assistance (Table 7-2). Drivers perceived situations with predictable lead vehicle behaviour as less hazardous and indicated a lower need for assistance than situations with unpredictable lead vehicle behaviour. The multivariate and univariate tests did not show significant interactions between predictability and level of assistance. Due to this result, the following results are reported for averaged values of drivers with and without FCAs. Paired *t*-tests were conducted to more specifically test the differences between predictable and unpredictable lead vehicle behaviour when the lead vehicle left the lane and the conflict dissolved (dashed lines in Figure 7-3). In line with Hypothesis 1a, drivers perceived the situation as significantly less hazardous in retrospect when they were able to anticipate that the lead vehicle will leave the lane than if not, $t\,(40) = 4.00$, $p < .001$ (one-tailed), $d_{Cohen} = 0.63$. With regard to Hypothesis 1b, drivers perceived a significantly lower need for assistance in predictable than in unpredictable situations, $t\,(40) = 1.81$, $p = .039$ (one-tailed), $d_{Cohen} = 0.28$. It needs to be considered that there was only a small-sized effect. Overall, the results supported Hypothesis 1.

This paragraph describes additional results of the analysis which are not directly related to Hypothesis 1. There were significant multivariate and univariate main effects of lead vehicle behaviour (Table 7-2). Participants perceived situations in which the lead vehicle stayed in the lane and the conflict remained as more hazardous and indicated a higher need for assistance than situations in which the lead vehicle left the lane and the conflict dissolved. Moreover, level of assistance had a marginally significant multivariate effect and a marginally significant univariate main effect on perceived need for assistance (Table 7-2). Drivers with FCAs perceived a higher need for assistance than drivers without FCAs.

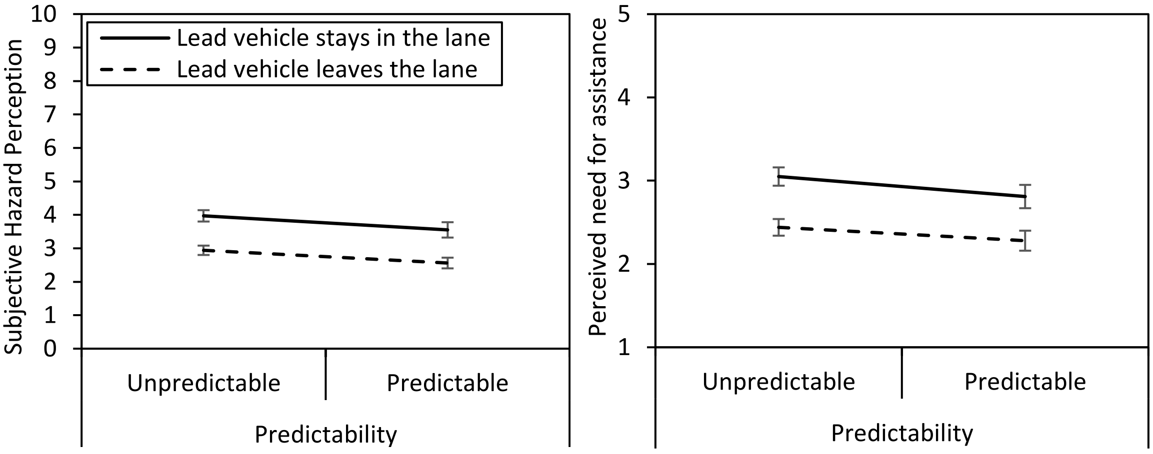

Figure 7-3. Means of subjective hazard perception (left) and perceived need for assistance (right) grouped by predictability and lead vehicle behaviour. Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

Table 7-2

Results of MANOVA with Relevant Multivariate and Univariate Effects of Predictability, Lead Vehicle Behaviour, and Level of Assistance on Subjective Hazard Perception and Perceived Need for Assistance

	df1	***df2***	**Wilks' λ**	***F***	***η_p²***
Multivariate effects					
Predictability	2	38	.79	5.10*	.21
Lead vehicle behaviour	2	38	.46	22.22***	.54
Level of assistance	2	38	.88	2.53†	.12
Predictability* Level of assistance	2	38	.91	1.90	.09
Univariate effects					
Subjective hazard perception					
Predictability	1	39		10.44**	.21
Lead vehicle behaviour	1	39		43.56***	.53
Level of assistance	1	39		0.64	.02
Predictability* Level of assistance	1	39		0.26	.01
Perceived need for assistance					
Predictability	1	39		5.22*	.12
Lead vehicle behaviour	1	39		36.04***	.48
Level of assistance	1	39		3.60†	.08
Predictability* Level of assistance	1	39		2.72	.07

Note. Without FCA: n = 19; with FCA: n = 22.
†$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

7.3.2 Alarm Acceptance

With regard to the second hypothesis, only data of the group with FCAs were considered. It was hypothesised that drivers evaluate FCAs in situations with dissolving conflict as less acceptable when they were able to anticipate the behaviour of the lead vehicle than if not. A repeated-measures ANOVA tested the impact of predictability and lead vehicle behaviour on alarm acceptance. Figure 7-4 illustrates the corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014). The analysis showed no significant main effect of predictability, $F(1, 21) = 1.89$, $p = .184$, $\eta_p^2 = .08$, and no significant interaction between predictability and lead vehicle behaviour, $F(1, 21) = 0.59$, $p = .451$, $\eta_p^2 = .03$. To test the difference between predictable and unpredictable lead vehicle behaviour when alarms were considered as unnecessary because the lead vehicle left the lane (dashed line in Figure 7-4), a paired *t*-test was conducted. In line with the second hypothesis, drivers evaluated an unnecessary alarm as less acceptable when they were able to anticipate that the lead vehicle will leave the lane than if they could not anticipate lead vehicle behaviour, $t(21) = 2.26$, $p = .018$ (one-tailed), $d_{Cohen} = 0.48$. Moreover, the ANOVA revealed a significant main effect of lead vehicle behaviour, $F(1, 21) = 17.22$, $p < .001$, $\eta_p^2 = .45$. Drivers evaluated FCAs as less acceptable when the lead vehicle left their lane and the conflict finally dissolved than when the lead vehicle stayed in their lane and the conflict remained. In accordance with the predefined classification of alarms as unnecessary or useful, drivers indicated a higher acceptance for useful alarms (lead vehicle stayed in the lane) than for unnecessary alarms (lead vehicle left the lane).

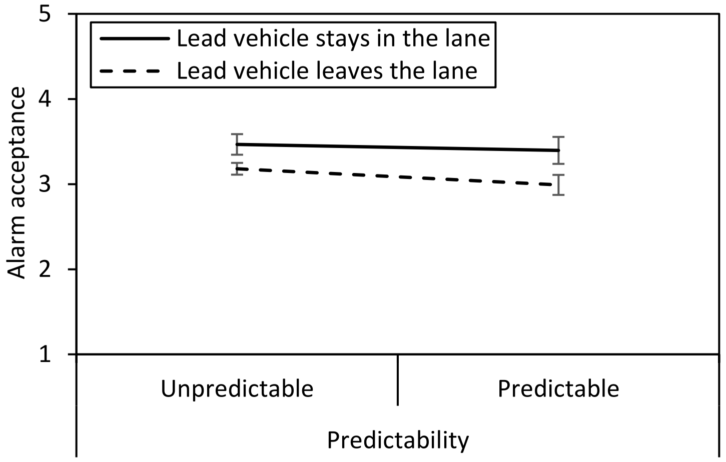

Figure 7-4. Means of alarm acceptance grouped by predictability and lead vehicle behaviour. Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

7.3.3 Driver Responses to Unnecessary Alarms

The analyses of driver responses only considered data of situations in which the lead vehicle left the lane and the potential conflict dissolved. Driver behaviour when receiving FCAs was compared to behaviour of drivers who experienced the same situation without FCA. A mixed MANOVA tested the impact of predictability and level of assistance on drivers' magnitude of speed reduction and maximum deceleration. Table 7-3 reports the test statistics of the multivariate and univariate tests and the right panel of Figure 7-5 illustrates the corresponding means and 95 % confidence intervals. Even though not further considered in the statistical analyses, the left panel of Figure 7-5 additionally shows the means and 95 % confidence intervals for the condition when the lead vehicle stayed in the lane and the conflict remained.

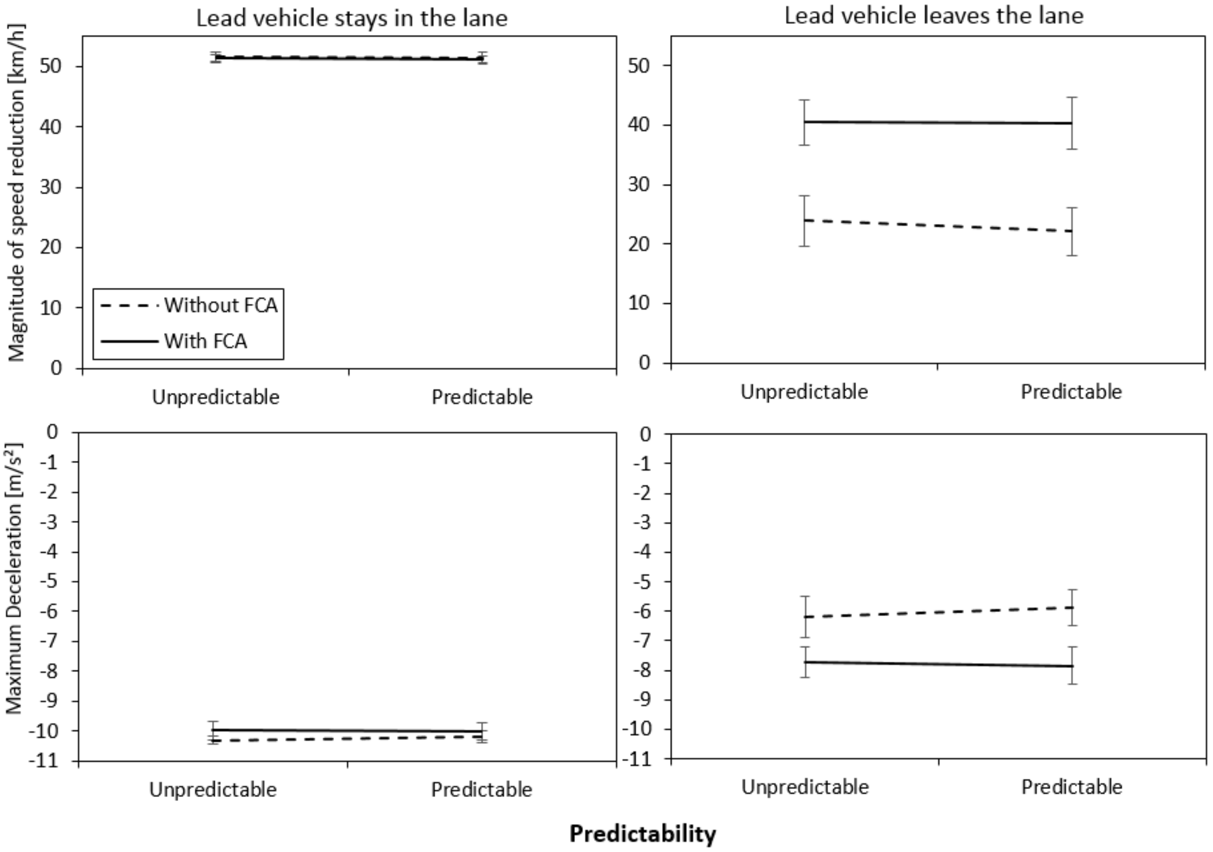

Figure 7-5. Means of magnitude of speed reduction (upper part) and maximum deceleration (lower part) grouped by lead vehicle behaviour, predictability, and level of assistance. Error bars display 95 % confidence intervals.

The MANOVA did not show a multivariate or univariate main effect of predictability (Table 7-3). To compare drivers' natural behaviour in response to a dissolving conflict dependent on the predictability of lead vehicle behaviour (Hypothesis 3a; dashed lines on the right side of Figure 7-5), two paired *t*-tests were additionally carried out. When the lead vehicle left the lane, drivers in the group without FCAs reduced their speed to an equal extent when they were able or not able to anticipate the behaviour of the lead vehicle, $t(18) = -1.11$, $p = .140$ (one-tailed), $d_{Cohen} = 0.28$. Drivers' maximum deceleration was marginally significantly lower when lead vehicle behaviour was predictable than when it was not predictable, $t(18) = 1.34$, $p = .099$ (one-tailed), $d_{Cohen} = 0.28$. Overall, the results did not support Hypothesis 3a.

Moreover, the MANOVA showed significant multivariate and univariate main effects of level of assistance (Table 7-3). In line with the first part of Hypothesis 3b, drivers who received an unnecessary alarm reduced their speed to a higher extent and decelerated more strongly than drivers who did not receive an alarm. However, there were no multivariate and univariate interactions between predictability and level of assistance (Table 7-3). Thus, the difference in driving behaviour with and without FCAs was not more pronounced when drivers were able to anticipate the behaviour of the lead vehicle than if not. Overall, the results partly supported Hypothesis 3b.

Table 7-3

Results of MANOVA with Multivariate and Univariate Effects of Predictability and Level of Assistance on Magnitude of Speed Reduction and Maximum Deceleration

	df1	*df2*	Wilks' λ	*F*	η_p^2
Multivariate effects					
Predictability	2	38	.98	0.41	.02
Level of assistance	2	38	.49	19.66***	.51
Predictability* Level of assistance	2	38	.94	1.21	.06
Univariate effects					
Magnitude of speed reduction					
Predictability	1	39		0.85	.02
Level of assistance	1	39		40.04***	.51
Predictability* Level of assistance	1	39		0.59	.02
Maximum deceleration					
Predictability	1	39		0.41	.01
Level of assistance	1	39		17.23***	.31
Predictability* Level of assistance	1	39		2.37	.06

Note. Without FCA: $n = 19$; with FCA: $n = 22$.
†$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

7.4 Discussion

The first goal of the third study was to investigate if drivers' ability to infer intentions of other road users and to anticipate their subsequent actions represents an advantage over the system on the anticipation level and results in a discrepancy between system risk assessment and drivers' subjective hazard perception. Moreover, the study aimed to gain further insights into drivers' acceptance of and responses to unnecessary alarms. Therefore, 41 participants encountered situations with a braking lead vehicle which would have resulted in consistently high risk assessments of conventional FCA systems and, thus, would have triggered FCAs. However, the subsequent action of the lead vehicle either resulted in a dissolving or remaining conflict. Drivers could either predict or not predict lead vehicle behaviour. One group of drivers received an FCA during each event and the other group experienced the same events without FCAs.

The results revealed that drivers' ability to predict the subsequent action of the lead vehicle decreased their retrospective subjective hazard perception and perceived need for assistance in comparison to situations with unpredictable lead vehicle behaviour. In line with the first hypothesis, drivers perceived situations in which the lead vehicle left the lane and the inter-vehicle conflict dissolved as less hazardous in retrospect and indicated a lower need for assistance if they were able to anticipate lead vehicle behaviour than if not. This finding also applied to situations in which the lead vehicle stayed in the lane and the conflict remained. Overall, a remaining conflict due to lead vehicle behaviour was perceived as more hazardous and was associated with a higher need for assistance than a dissolving conflict. Independent of their prior ability to predict lead vehicle behaviour, drivers perceived a situation that included an emergency stop as more hazardous in retrospect and had a higher need for assistance than a situation that would not have required a braking reaction. To sum up, the findings suggest that drivers were presumably able to infer the intention of the lead vehicle's driver and the corresponding subsequent action from environmental cues. They used schemata stored in long-term memory that include possible actions associated with the context in which the lead vehicle's behaviour of signalling and braking was embedded (Stahl, 2015; Zunino et al., 2017). This ability allowed them to predict if the potential inter-vehicle conflict would finally dissolve or remain. Their anticipation determined their retrospective subjective hazard perception and perceived need for assistance. Conventional FCA systems do not consider these additional information to comprehend the situation and to predict the other road users' status in the near future. Instead, the system's prediction is usually exclusively based on TTC values concerning the ego vehicle and the potential conflict partner. Therefore, the results of this study corroborate Hypothesis IIIb derived from the theoretical framework. Drivers' advantage over the system to anticipate a dissolving conflict by considering intentions attributed to other road users can be identified as additional factor that causes discrepancies between human subjective hazard perception and system risk assessment. According to the results, this discrepancy would be less pronounced if neither the system nor the driver were able to predict that a potential inter-vehicle conflict would finally remain. In contrast, a dissolving conflict that was already predictable for the human driver would cause the greatest discrepancy. Studies 1 and

2 showed that subjective hazard perception predicts perceived need for assistance. Even though the third study did not explicitly test this relationship, it demonstrated that predictability and lead vehicle behaviour had a similar impact on perceived need for assistance as on subjective hazard perception. It should be noted that ratings for subjective hazard perception and need for assistance were relatively low in all condition combinations. On average, situations were perceived as harmless to uncomfortable and perceived need for assistance received ratings between 2 and 3 on a 5-point Likert scale. A possible explanation for this finding might be that drivers did not perceive TTC values of at least two seconds as very hazardous. However, in the setting of the present study, it was not possible to realize more critical TTC values. In the condition in which the lead vehicle left the lane, it was necessary that participants were able to drive on at constant speed of 50 km/h without causing a collision. This would not have been possible with smaller TTC values. Moreover, some participants reported that they did not perceive the encountered situations as very hazardous as they were quite similar to situations they frequently experience during daily driving.

The findings concerning drivers' acceptance of unnecessary alarms supported the second hypothesis. Alarms were predefined as unnecessary when the lead vehicle left the lane and the conflict dissolved. In these situations, drivers evaluated unnecessary alarms as less acceptable when they were able to anticipate the subsequent action of the lead vehicle than if anticipation was not possible. Thus, drivers' acceptance of unnecessary alarms was lower when they had an advantage over the system on the anticipation level than when neither they nor the system were able to predict a dissolving outcome of the conflict. This finding might explain why unnecessary alarms did not decrease perceived ease of use, usefulness, and trust in comparison to a perfectly reliable system in the study by Naujoks et al. (2016). In their study, drivers were not able to anticipate subsequent actions of other road users. Overall, drivers of the present study indicated a higher acceptance for useful alarms (lead vehicle stayed in the lane) than for unnecessary alarms (lead vehicle left the lane). This finding was in line with the results of Study 2. In general, participants' acceptance of alarms was rather ambivalent as their ratings varied in the middle range. This finding could be also associated with the FCA activation threshold of two seconds and that drivers felt that situations were quite similar to frequently experienced situations in real traffic.

With regard to driving behaviour, the present study first examined the impact of drivers' ability to predict that the lead vehicle will leave the lane and the conflict dissolves on their natural driving behaviour without FCAs. The results contradicted Hypothesis 3a and suggested that drivers' magnitude of speed reduction and maximum deceleration did not differ dependent on their ability to predict lead vehicle behaviour. Moreover, the study compared driving behaviour in response to unnecessary FCAs to drivers' natural behaviour in the same situations without FCAs. In line with Hypothesis 3b, drivers who received unnecessary FCAs reduced their speed to a higher extent and decelerated more strongly than drivers who experienced the same situation without FCAs. However, the difference in driving behaviour with and without FCAs was not more pronounced in presence of environmental cues that allowed to anticipate a dissolving conflict than when the cues were occluded. This finding might be explained by the fact that drivers were able to consider the dynamic course of the traffic situations for their actions (Endsley, 1988). Even if a dissolving outcome of a potential conflict was not predictable, they seem to have constantly adjusted their situation awareness. In the moment the lead vehicle left their lane, drivers dynamically adjusted their actions and released the brake pedal. The finding that unnecessary alarms caused stronger driver responses than the same situation without alarms was in line with Study 2 of this thesis and the study by Lees and Lee (2007). Thus, there is further evidence for the assumption that the process of cross-checking the validity of an unnecessary alarm might be very demanding without prior experience with situations typically associated with unnecessary alarms (Gérard & Manzey, 2010). As driver responses in situations with predictable dissolving outcome were more intense in the present study than in Study 2, it is assumed that the validation of unnecessary alarms in the present study might have been more demanding. First, drivers might have been more confident about their own manoeuvre intentions than about inferred intentions of other road users. Thus, they seem to have considered the estimated reliability of their current anticipations for their action selection. Second, a potential methodological limitation of the present experiment was a very short time frame to actively perceive and comprehend the environmental cues that served to predict lead vehicle behaviour. When approaching the intersection, drivers were already able to perceive the pedestrian at the crosswalk or the bus at the bus station some seconds before the lead vehicle started to brake. Nevertheless, these cues only became relevant at the moment the lead vehicle activated its turn indicator 400 milliseconds before it finally braked. The assumption that this short time frame limited the predictability is supported by the finding that even under natural driving conditions, drivers reduced their speed and decelerated to an equal extent with and without the possibility to predict a dissolving conflict. Study 4 will investigate if increasing experience with unnecessary alarms might simplify the process of cross-checking the validity of unnecessary alarms and, thus, reduces the intensity of driver responses to unnecessary alarms.

A further potential limitation could have been that drivers might have perceived the lead vehicle's driving behaviour as unnatural. The lead vehicle braked abruptly during each test event in order to achieve equal TTC values in both conditions of lead vehicle behaviour. However, the fast changeover between braking, standing for 150 ms, and reaccelerating when the lead vehicle stopped to leave the lane might have been irritating. Therefore, lead vehicle behaviour might have been hard to predict even in the predictable condition. Under real traffic conditions, a predictable dissolving conflict would be mainly caused by drivers who intentionally approach a *standing* lead vehicle at constant speed that is about to turn out of their lane. Drivers would provoke such a situation when having enough time to collect relevant environmental cues that enable them to anticipate that the lead vehicle will have turned out of the lane until this place is reached. In contrast, in the experimental setting, drivers were actively forced into the traffic situation with dissolving conflict. Future research should develop more realistic traffic scenarios to examine the impact of the predictability of subsequent actions of other road users on subjective hazard perception, need for assistance, alarm acceptance, and driving behaviour. This could reveal even larger effects on the studied variables.

7.5 Conclusion

This study gained insights into assumptions derived from the theoretical framework of drivers' subjective alarm evaluation. The results showed that drivers' subjective hazard perception and perceived need for assistance varied dependent on their ability to anticipate a dissolving outcome of a potential inter-vehicle conflict. To anticipate the further course of a traffic situation, drivers do not only consider their own subsequent actions based on their current manoeuvre intention (see Studies 1 and 2), but also subsequent actions of other road users. Drivers are able to anticipate actions of other road users by inferring their current intentions from cues in the environment in which their actions are embedded. Concurrently, the system only considers the TTC between ego vehicle and the potential conflict partner to predict the further course of the situation. When drivers have an advantage over the system in anticipating a dissolving outcome of a potential conflict based on the intention attributed to the potential conflict partner, the system's risk assessment is finally higher than drivers' retrospective subjective hazard perception. As a consequence, the system would activate an alarm while drivers have a low need for assistance. Under these conditions, drivers perceive alarms as unnecessary.

Moreover, the study provided knowledge about drivers' acceptance of unnecessary alarms. Drivers perceived unnecessary alarms as more acceptable when they could not anticipate the subsequent action of the lead vehicle than when they already knew that the conflict would dissolve. Thus, unnecessary alarms seem to be more pardonable when drivers do not have an advantage over the system in anticipating a dissolving outcome of the conflict.

The study gained additional insights into short-term effects of unnecessary alarms on driver responses. Drivers with unnecessary alarms reduced their speed to a higher extent and decelerated more strongly than drivers who showed their natural driving behaviour in the same situations without alarms. This finding did not differ dependent on drivers' ability to anticipate lead vehicle behaviour that resulted in a dissolving conflict. The results supported the findings of Study 2. Thus, in the short term, unnecessary alarms seem to result in driver responses of moderate intensity even if drivers are principally able to anticipate a dissolving outcome of the conflict.

8 Study 4: Evaluation of Adaptive Alarm Systems

8.1 Introduction and Research Questions

The previous three studies of this thesis provided insights into factors that determine drivers' retrospective subjective hazard perception of potential collision situations and, thus, their perceived need for assistance. It has been found that drivers perceive alarms as rather unnecessary when their retrospective subjective hazard perception was lower than the system risk assessment. Such a discrepancy resulted from advantages of the driver over the system in anticipating a dissolving outcome of a potential conflict. In contrast to the system whose prediction is based on physical measurements alone, drivers' anticipation additionally considered their own manoeuvre intentions and anticipated intentions of other road users. Moreover, drivers accepted alarms which they have classified as useful more than alarms classified as unnecessary. Drivers' classification was largely accompanied by their advantages in anticipating a remaining or dissolving outcome of a potential conflict.

Study 4 applied these findings in order to evaluate two different adaptive FCA systems in terms of their effects on system acceptance, trust, reliability, and understanding. In contrast to previous studies on adaptive systems, the adaption strategy in the present study was associated with drivers' actual perceived need for assistance based on empirical results of this thesis. To keep the complexity of the alarm activation strategy low, the systems were only adapted to one further parameter apart from physical measurements (TTC). Based on the findings of Study 1 and 2, the adaptive FCA systems used drivers' current manoeuvre intention as adaption parameter. FCAs were considered as unnecessary when drivers' intended manoeuvre did not interfere with the traffic event, and as useful when there was an interference between manoeuvre intention and traffic event. Therefore, the systems activated imminent FCAs only in the latter case. The first adaptive system adopted a negative adaption strategy (see Section 2.4.1). It suppressed alarms that were deemed unnecessary and, thus, reduced the rate of unnecessary alarms and the total number of alarms. With this adaption strategy, the mapping between events in the environment and alarm occurrence could be more complex than for a non-adaptive system (Smith et al., 2008). As similar external events sometimes activate an alarm and sometimes not, drivers might perceive the system behaviour as inconsistent. Therefore, the basic adaptive system could interfere with the development of a correct mental model of the alarm system. As a consequence, positive effects of the adaptive system on drivers’ subjective system evaluations might be cancelled out by negative effects of drivers’ incorrect mental model. The underlying logic of alarm activation might be more transparent with a neutral adaption strategy than with a negative strategy (Smith et al., 2008). Thus, the second adaptive system in the current study adopted a modification of a neutral adaption strategy. Instead of adapting the alarm design to drivers’ need for assistance, the system displayed the explanation for alarm suppression in the HUD. With this strategy, the system was still able to reduce the total number of activated alarms, while it aimed at supporting the development of drivers’ mental model. In summary, one adaptive system simply suppressed unnecessary alarms (basic adaptive system), while the other adaptive system displayed an explanation when alarms were suppressed (explanatory adaptive system). The adaptive systems were compared to a conventional non-adaptive FCA system (standard system) whose prediction, risk assessment, and, thus, alarm activation was based on physical measurements (TTC) alone. Based on the outlined assumptions and on the results of the previous studies of this thesis, it was hypothesised that drivers’ perceived system understanding of the basic adaptive system is worse than that of the standard system and the explanatory adaptive system (**Hypothesis 1**). The explanation for alarm suppression was assumed to improve the development of drivers’ mental model compared to a negative adaption strategy without explanation (**Hypothesis 2**). **Hypothesis 3** proposed that increasing system experience would increase drivers’ perceived system understanding of all FCA systems. Even if drivers might have difficulties to understand the functioning of the basic adaptive system, they presumably perceive higher trust in this system than in the standard system that activates many unnecessary alarms, while the trust in the explanatory adaptive system is expected to be the highest (explanatory adaptive > basic adaptive > standard; **Hypothesis 4**). Furthermore, it was hypothesised that system trust in both adaptive systems would increase with increasing system experience, while trust in the standard system remains at a constant level (**Hypothesis 5**). With regard to perceived system reliability and system acceptance, the same ranking as for perceived reliability (explanatory adaptive > basic adaptive > standard) was assumed (**Hypothesis 6** and **Hypothesis 7**).

Furthermore, the study investigated how responses to unnecessary alarms develop with multiple encounters. The results of Study 2 and 3 revealed short-term effects of unnecessary alarms on driver responses. Drivers who received unnecessary FCAs reduced their speed to a higher extent and decelerated more strongly than drivers who experienced the same situation without FCAs. However, based on the results of the naturalistic driving studies by Flannagan et al. (2016) and General Motors Corporation (2005), drivers' responsiveness to unnecessary alarms was expected to decrease with increasing system experience. It was assumed that the process of cross-checking the validity of an unnecessary alarm is demanding without prior experience with situations that usually activate unnecessary alarms (Gérard & Manzey, 2010). To avoid the risk of a missing necessary alarm response, a moderate braking response appears to have the lowest probability of a negative outcome. However, with increasing system and alarm experience, drivers might develop a schema consisting of traffic constellations that typically activate unnecessary alarms. When already expecting a potential alarm activation, drivers might need less cognitive resources to cross-check the validity of an unnecessary alarm. During this learning process, drivers might learn to select a less intense alarm response or to not respond to the alarm. Therefore, the present study tested the hypothesis that drivers' responses to unnecessary alarms decrease as the number of encounters with unnecessary alarms increases (**Hypothesis 8**). It was assumed that the difference in driver behaviour in response to unnecessary alarms and without receiving alarms becomes less pronounced with multiple exposures to traffic situations in which their manoeuvre intention cause a dissolving outcome (**Hypothesis 9**).

8.2 Method

8.2.1 Participants

A total of 45 participants (22 female, 23 male) took part in the study. Seven participants had to be excluded from data analysis, one person due to simulator sickness, two persons due to technical problems with the simulation software, one person due to technical problems with the tablet used for questionnaires, and two persons drove too slowly in more than the half of all test events (see Section 8.2.7). The remaining 38 participants (18 female, 20 male) were between 21 and 65 years old (*M* = 39.53, *SD* = 14.87). Participants stated to cover *M* = 20,026 kilometres per year (*SD* = 19,265) and to have held their driver's license for *M* = 20.79 years (*SD* = 14.05). On average, they had already experienced a few FCAs before their participation in the experiment, *M* = 2.14, *SD* = 0.98 (1 = *never*, 2 = *1 to 3 times*, 3 = *more than 3 times*, 4 = *on a regular basis*). However, only 4 % of the participants have gained this experience in a private or company car, while 64 % have experienced FCAs only during driving studies and 32 % in both contexts. Participants were recruited from the WIVW driver test panel. Each of them had received at least four hours simulator training in two training sessions (Hoffmann et al., 2003). The rationale behind this training is explained in Section 5.2.1.

8.2.2 Apparatus

The study was conducted in the driving simulator at WIVW GmbH (see Section 4.1).

8.2.3 Experimental Design

The experiment used a 2x3 mixed design with the within-subject factor manoeuvre intention and the between-subject factor FCA system. To manipulate manoeuvre intention, a navigation system provided auditory and visual announcements. Dependent on participants' current manoeuvre intention, the encountered traffic event either interfered (a) or did not interfere (b) with their executed driving manoeuvre (Figure 8-3). The factor FCA system was represented by either driving with a standard (non-adaptive) system (a), an adaptive system (b), or an explanatory adaptive system (c). Based on the findings of Study 1 and partly of Study 2, FCAs were considered as unnecessary when drivers' manoeuvre did not interfere with the traffic event and as useful when manoeuvre intention and traffic event interfered. This assumption was confirmed by the results of a manipulation check (see Section 8.3.1). With the standard system, participants received an equal amount of unnecessary (8) and useful (8) FCAs throughout the experiment (16 FCAs in total). More specifically, the system activated an FCA every time the TTC with another road user fell below 1.95 seconds. The system did not consider drivers' current manoeuvre intention for alarm activation. In contrast, the adaptive system activated FCAs dependent on the current TTC in combination with drivers' current manoeuvre intention. FCAs were activated when TTC values fell below 1.95 seconds *and* the traffic event interfered with their intended driving manoeuvre. As soon as drivers' manoeuvre intention did not interfere with the traffic event, the system suppressed the FCA. Therefore, the adaptive system activated eight useful FCAs and suppressed eight unnecessary alarms. The activation strategy of the explanatory adaptive system was basically similar to that of the adaptive system. Instead of just suppressing the FCA, the system displayed the explanation for alarm suppression in the HUD (Figure 8-1). The pop-up appeared at the same moment in which the standard system activated the FCA (TTC = 1.95 sec) and disappeared after five seconds. Figure 8-2 illustrates the different activation strategies of the three FCA systems. The FCA modality is described in Section 4.2. Subjects were quasi randomly allocated to the three FCA systems (standard *n* = 12, adaptive *n* = 13, explanatory adaptive *n* = 13). To obtain groups of approximately equal size, the number of participants randomly assigned to each FCA system was limited.

Collision alarm suppressed:
Intention to turn detected

Figure 8-1. Pop-up notification in the HUD used for the explanatory adaptive system.

To reduce carry-over from one event to another and to increase the number of measurement points, participants encountered two different traffic scenarios each with four different environments and two manoeuvre intentions (2 (traffic scenario) x 4 (environment) x 2 (manoeuvre intention) = 16 test events). Additionally, the study included 16 filler events. Thus, all participants encountered 16 test events plus 16 filler events that varied according to manoeuvre intention. Section 8.2.4 describes the realisation of both test and filler events. The 16 test events were divided into four driving blocks. Each block consisted of two events of the first and two events of the second traffic scenario (see Section 8.2.4), in each case with both levels of manoeuvre intention. Additionally, each block included four filler events which were randomly allocated between the test events. To control for transition effects, the position of the four blocks was counterbalanced to four different sequences. To obtain equal group sizes, subjects were quasi randomly distributed to the four sequences with a cell size of *n* = 9 — 10 drivers. Thus, the number of participants randomly assigned to each sequence was limited.

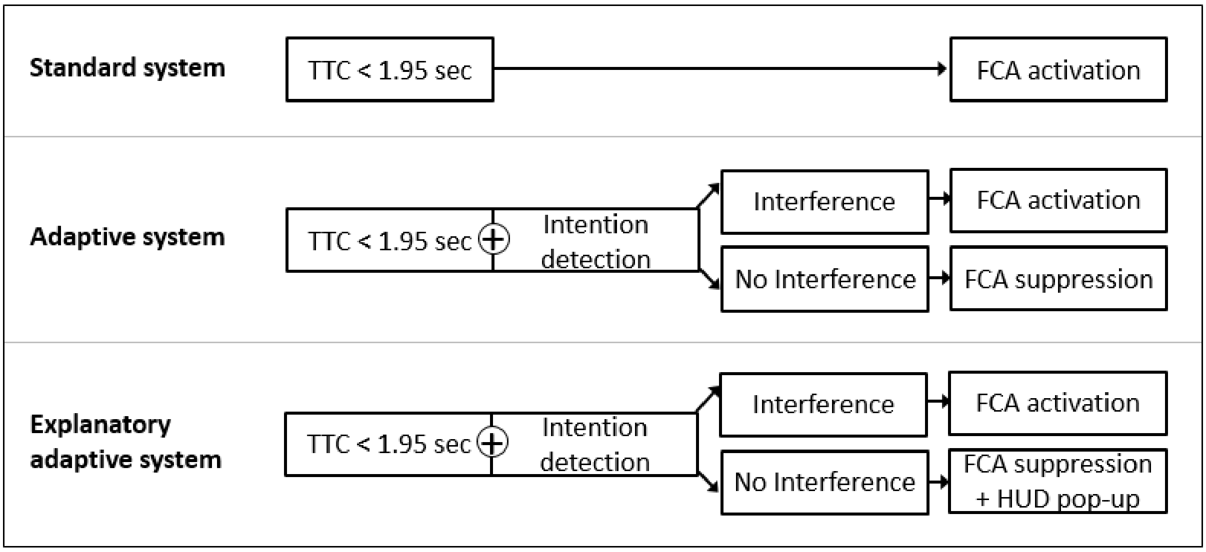

Figure 8-2. Activation strategies of the three FCA systems used in Study 4.

8.2.4 Traffic Scenarios

The entire simulation drive took place in an urban environment with a speed limit of 50 km/h. To attain equal velocity conditions between different participants and traffic scenarios, participants used a speed limiter with a maximum velocity of 50 km/h. They drove through streets with regular turning-off streets, parked vehicles at the roadside, and pedestrians at the sidewalk.

Participants encountered both levels of manoeuvre intention with two different traffic scenarios. In the first traffic scenario (lead vehicle), participants followed a lead vehicle that suddenly braked to a standstill at a certain point while there was a turning street on the right. Dependent on their current manoeuvre intention, participants either intended to stay behind (interference) or to turn directly behind the braking lead vehicle (no interference). In the second traffic scenario (intersection), another road user approached an intersection from the right and took the ego driver's right of way who was driving on the main road. Participants either intended to stay on the main road (interference) or to turn to the right (no interference). Each traffic scenario was realized with four different environments. Figure 8-3 illustrates the two different traffic scenarios each with two examples for different environments and both levels of manoeuvre intention. The environments differed according to buildings, plants, and other objects (e.g. street lamps, benches, parasols) on the side of the road before and during the traffic event, the colours and models of the lead vehicle, and the type of road user who approached the intersection (car, motorbike, or van). The intent to vary the environment of only two traffic scenarios instead of using eight different traffic scenarios was to decrease the variance between different scenario types while still reducing carry-over effects and increasing the number of measurement points. In each test event, the TTC fell below 1.95 seconds. For the calculation of the TTC values, Equation 1 in Section 4.2 was used.

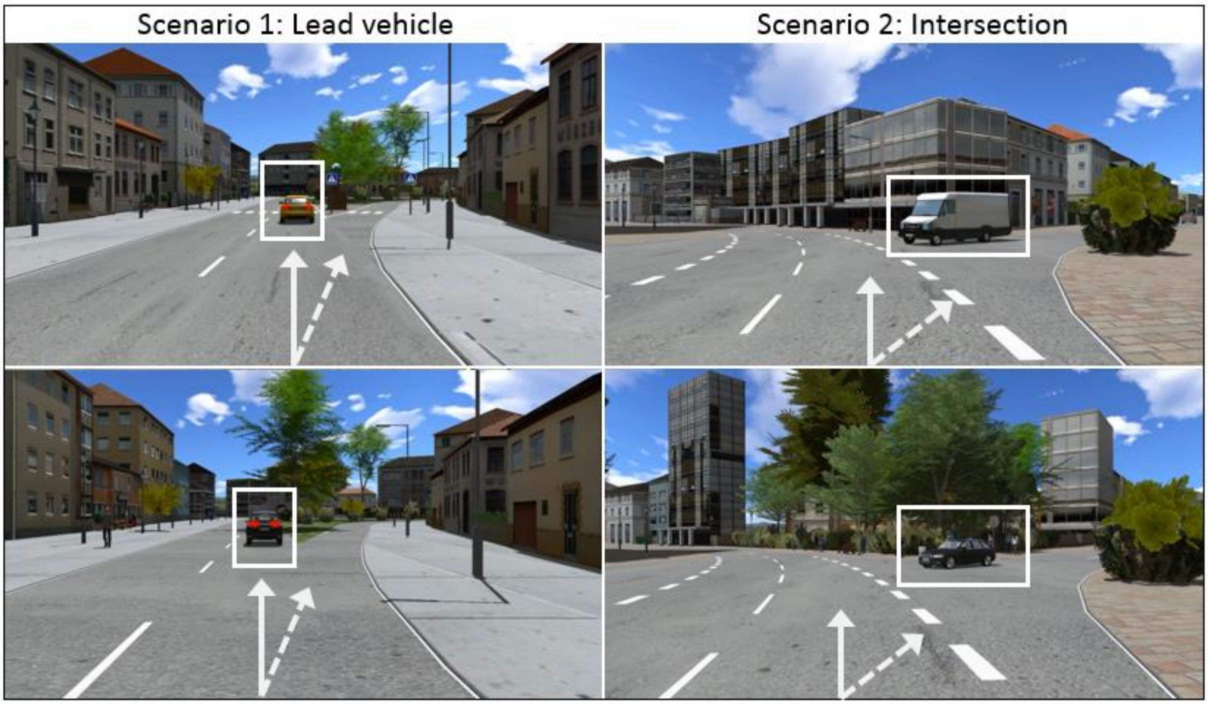

Figure 8-3. Realization of manoeuvre intention in both traffic scenarios each with two examples of different environments. Conflict partner is marked by a frame. Solid line: event interferes with intended manoeuvre; dashed line: event does not interfere with intended manoeuvre.

In the filler events, environments did not differ from those of the test events. However, in the lead vehicle scenario, the lead vehicle continued driving and did not decelerate at a certain point. In the intersection scenario, the other road user stopped at the intersection instead of taking the ego drivers' right of way. Therefore, TTC values never fell below 1.95 seconds.

8.2.5 Dependent Measures

As a manipulation check, participants evaluated the FCA usefulness after each encountered test event. When a test event was accompanied by an FCA, the item that was introduced by the statement "In this traffic situation, the collision warning was useful" and without having experienced an FCA, it was introduced by "[…], a collision warning would have been useful". Participants gave their answer verbally through an intercom on a 6-point Likert scale (1 = *strongly disagree,* 2 = *disagree,* 3 = *rather disagree,* 4 = *rather agree,* 5 = *agree,* 6 = *strongly agree*). The scale was printed on a piece of paper and attached to the steering wheel.

All other items were presented and answered on a tablet (see Section 4.1). After each of the four driving blocks, participants were asked to indicate their system trust and system understanding. System trust and system understanding were assessed with two scales of the "Trust in Automation" questionnaire (TIA) by Körber (2015) using a 6-point Likert scale (1 = *strongly disagree,* 2 = *disagree,* 3 = *rather disagree,* 4 = *rather agree,* 5 = *agree,* 6 = *strongly agree*). Two items served to measure system trust (e.g. "I trust the system"; mean internal consistency α = .90) and five items measured system understanding (e.g. "It is difficult to identify what the system will do next"; mean internal consistency α = .78).

At the end of the experiment, participants indicated their overall impression and evaluation of the FCA system with regard to system trust, system understanding, system reliability, and system acceptance. All items used a 6-point Likert scale (1 = *strongly disagree,* 2 = *disagree,* 3 = *rather disagree,* 4 = *rather agree,* 5 = *agree,* 6 = *strongly agree*). Overall system trust was measured with nine items of the trust in automated systems scale by Jian, Bisantz, and Drury (2000) (e.g. "The system behaves in an unhanded manner"; internal consistency α = .95). Items were presented in German language (translated by Beggiato (2015)). Overall system understanding was measured with the same items as those used in the interim questionnaires (internal consistency α = .88). System reliability was also assessed with a scale of the TIA (Körber, 2015) consisting of six items (e.g. "The system is capable of interpreting situations correctly"; internal consistency α = .83). To measure system acceptance, four scales based on the technology acceptance model were used and adapted (Davis, 1989; Davis, Bagozzi, & Warshaw, 1989). Participants assessed perceived usefulness on five items (e.g. "Using the FCA system improves driving"; internal consistency α = .88) and perceived ease of use on three items (e.g. "My interaction with the FCA system was clear and understandable"; internal consistency α = .59). Behavioural intention to use the system was measured by one item ("I would intend to use such a system, if I had the chance to") and attitude towards behaviour by two items (e.g. "I like the idea of using the FCA system"; internal consistency α = .82) (Taylor & Todd, 1995). All items were presented in German language (translated by Jung, Kaß, Zapf, and Hecht (2019)).

Table 8-1

Items of the Mental Model Questionnaire

The FCA system …	Never true	Some-times true	Always true
… considers my planned driving way for warning activation.	0	0	1
… suppresses certain warnings dependent on my planned driving way.	0	0	1
… does not warn in low-light conditions.	1	0	0
… activates a warning every time a lead vehicle brakes strongly.	1	1	0
… activates a warning every time another road user approaches an intersection quickly.	1	1	0
… is not able to detect every braking lead vehicle.	1	0	0
… works only with little traffic.	1	0	0
… does not activate a warning if the radar sensor is dirty.	1	0	0
… does not activate a warning in low light conditions.	1	0	0
… only warns of vehicles above a certain size.	1	0	0

Note. 0 = incorrect answer; 1 = correct answer.

To measure participants' mental models of the activation strategies of the two adaptive FCA systems, an open-ended question and a self-developed questionnaire were used. The open-ended question and the items were only presented to those participants who drove with one of the adaptive systems. The question was "Please explain in your own words in which situations the collision warning system has activated warnings. Why did the system suppress certain warnings?". The additional questionnaire was adapted from Beggiato (2015) who developed a standardised questionnaire to assess drivers' mental model of adaptive cruise control. In contrast to conventional and well-known qualitative methods to measure mental models (e.g. card sorting; Cherri, Nodari, & Toffetti, 2004), this approach allowed to statistically analyse differences in the mental models of participants who used different FCA systems. The adapted version consisted of nine self-developed items about alarm activation and of nine additional self-developed items concerning general system understanding. However, the items about general system understanding (e.g. "The FCA system detects an impending collision with another road user") only served to direct participants' focus of attention away from the items of interest about alarm activation. Participants had to select one answer option out of *never true*, *sometimes true*, and *always true*. Correct answers received 1 point and incorrect answers 0 points. For some items, two options were accepted as correct. Table 8-1 includes all items concerning alarm activation and the coding for correct and incorrect answers.

To measure driver responses to the test events, the magnitude of speed reduction and maximum deceleration were measured (see Section 4.3).

8.2.6 Procedure

The Ethics Committee of the Institute for Psychology of the Julius-Maximilians-University Würzburg has declared the study to be ethically unobjectionable. Upon arrival, participants received written instructions containing information about the purpose of the study, the simulation environment, the speed limit of 50 km/h, and driving with a speed limiter. They were informed that the study examines different types of FCA systems. They did not receive an explanation of the implemented activation strategies. Additionally, participants signed a consent form that informed them about their right to decline to participate and to withdraw from the study at any point, and the method of data anonymization.

The experimental drive consisted of four driving blocks. At the end of each driving block, there was a programmed announcement that said “Please stop here”. After having stopped, drivers answered the interim questionnaire concerning the most recently encountered driving block on the tablet. After that, they started driving again and experienced the next driving block. After the fourth driving block, they additionally answered the final questionnaire on the tablet. Overall, the study took about 1.5 hours per participant. At the end of the experiment, participants were thoroughly debriefed.

8.2.7 Data Analysis

The hypotheses were tested with one-way, repeated-measures, and mixed ANOVAs and MANOVAs. Post-hoc tests were calculated with paired *t*-tests. All analyses were carried out using IBM SPSS statistics software (Version 22). The significance level was set at $\alpha = 0.05$.

To analyse the answers to the mental model questionnaire, the correct answers per scale were added up to a score that reflected the quality of the mental model. The maximum score that could be achieved was 9. For both adaptive FCA systems, the average score of all participants who used the system was calculated. Then, the means of both adaptive FCA systems were compared with a one-way ANOVA.

A criterion for excluding measurement points of driving data and ratings for FCA usefulness (manipulation check) from data analysis was a velocity slower than 34 km/h at the moment the lead vehicle started to brake or the other road user took the ego driver’s right of way at the intersection. When drivers approached the intersection at a slower speed, the coordinates of the ego vehicle and the other road user showed that the other road user already crossed the ego vehicle’s way and, therefore, no longer posed a crash risk. For consistency reasons, this velocity criterion was also adopted to the lead vehicle scenario. In total, 46 measurement points (out of 608 measurement points in total) of 23 different participants were excluded from data analysis. The maximum number of excluded measurement points per participant was five. Table 8-2 provides an overview of the excluded measurement points grouped by traffic scenario and manoeuvre intention. As already mentioned in Section 8.2.1, complete data sets of two participants were additionally excluded as they drove too slowly in at least half of all test events. Measurement points of the other subjective ratings were not affected as they were related to driving blocks or the entire simulation drive.

Table 8-2

Overview of Excluded Measurement Points Grouped by Traffic Scenario and Manoeuvre Intention

	No manoeuvre interference	Manoeuvre interference
Traffic scenario	*n*	*n*
Lead vehicle	3	22
Intersection	18	3
Sum of excluded measurement points = 46	∑ = 21	∑ = 25

8.3 Results

8.3.1 Manipulation Check

To ensure that the predefined classification of alarms as useful during events with manoeuvre interference and as unnecessary during events without manoeuvre interference matched drivers’ subjective ratings of FCA usefulness, a mixed ANOVA with manoeuvre intention and traffic scenario as within-subject factors and FCA system as between-subject factor was carried out. Figure 8-4 illustrates the corresponding means and 95 % confidence intervals. The analysis revealed a significant main effect of manoeuvre intention on FCA usefulness, $F(1, 33) = 698.14$, $p < .001$, $\eta_p^2 = .96$. Drivers perceived alarms as significantly more useful when the traffic event interfered with their manoeuvre intention than without interference.

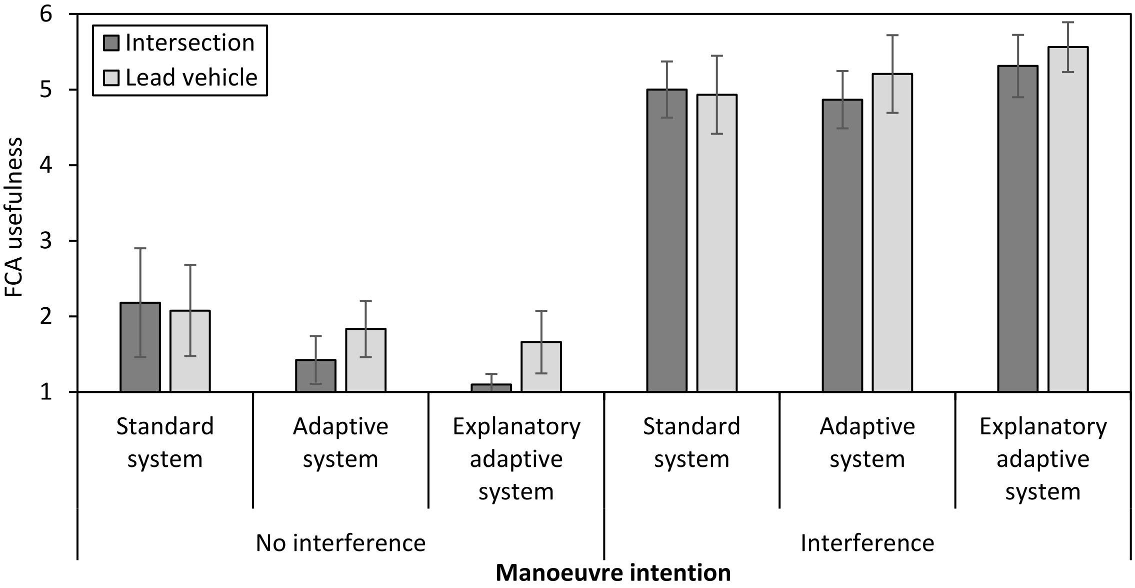

Figure 8-4. Means of FCA usefulness grouped by manoeuvre intention, FCA system, and traffic scenario. Error bars display 95 % confidence intervals.

Moreover, there was a significant interaction between manoeuvre intention and FCA system, $F(2, 33) = 7.06$, $p = .003$, $\eta_p^2 = .30$. When drivers' manoeuvre intention did not interfere with the traffic event, post-hoc tests with Bonferroni adjustments showed that the standard system that activated FCAs in these situations was perceived as more useful than the explanatory adaptive system that did not issue FCAs ($p = .018$). Furthermore, drivers rated FCAs as significantly more useful during the lead vehicle scenario than during the intersection scenario, $F(2, 33) = 4.34$, $p = .045$, $\eta_p^2 = .12$. To sum up, the results of the manipulation check confirmed the use of manoeuvre intention as adaption parameter.

8.3.2 Subjective System Understanding and Mental Model

To test if drivers' perceived system understanding of the basic adaptive system is worse than that of the standard system and the explanatory adaptive system (Hypothesis 1), a one-way ANOVA with FCA system as factor and overall system understanding as dependent variable was conducted. Figure 8-5 displays the corresponding means and 95 % confidence intervals. There was no significant main effect of FCA system, $F(2, 35) = 1.66$, $p = .205$, $\eta_p^2 = .09$. The descriptive data showed that the difference between the standard and adaptive FCA system was pronounced the opposite direction than assumed in the hypothesis. Overall, the results did not support the first hypothesis.

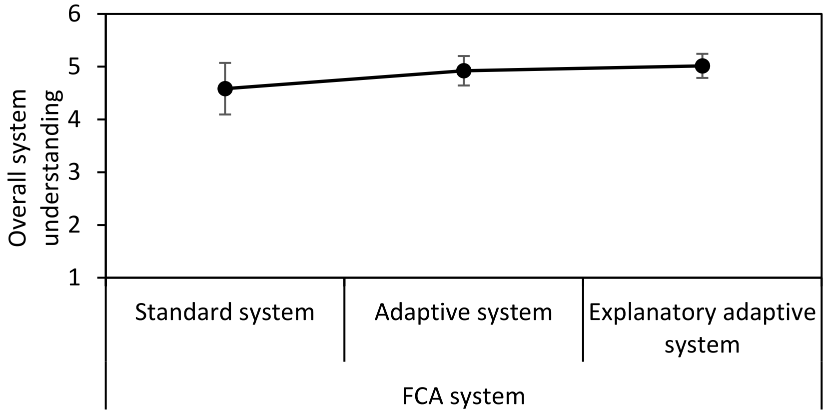

Figure 8-5. Means of overall system understanding grouped by FCA system. Error bars display 95 % confidence intervals.

The second hypothesis proposed that the mental model of the explanatory adaptive system would be better than that of the basic adaptive system. A one-way ANOVA with FCA system (adaptive versus explanatory adaptive) as factor and mental model as dependent variable was conducted. The analysis did not show a significant difference between the mental model of the adaptive ($M = 6.15$, $SD = 1.82$) and that of the explanatory adaptive system ($M = 6.00$, $SD = 1.63$), $F(1, 24) = 0.50$, $p = .411$, $\eta_p^2 = .002$. To more specifically analyse if drivers understood the relevance of manoeuvre intention as adaption parameter, the ANOVA was repeated with the score of only the first two items of the questionnaire as dependent variable (Table 8-1). Accordingly, the score could only range between 0 and 2, instead of between 0 to 9. The results did not show a significant difference between the mental model of the adaptive ($M = 1.15$, $SD = 0.90$) and that of the explanatory adaptive system ($M = 1.38$, $SD = 0.77$), $F(1, 24) = 0.50$, $p = .244$, $\eta_p^2 = .02$. To gain more insights into drivers' mental model of the adaption parameter, the results of the questionnaire were extended by a qualitative analysis of participants' answers to the open-ended mental model question. Therefore, each open answer was categorized as either correct or incorrect. Answers were categorized as correct if participants' explanations included the key words "intention to turn", "intention detection", "turn intention", "driver intention", "turn manoeuvre", or "leave common driving way". Three participants with the adaptive system and one participant with the explanatory adaptive system did not answer to this question. In the group with the adaptive system, seven participants gave a correct answer and in the group with the explanatory adaptive system, nine participants answered correctly. In each group, there were three participants who gave an incorrect answer. Based on the results of the quantitative as well as of the qualitative analysis, the hypothesis that the mental model for the explanatory adaptive system would be more correct than that for the basic adaptive system had to be rejected.

To test the impact of system experience on perceived system understanding (Hypothesis 3), a mixed ANOVA with position as within-subject factor and FCA system as between-subject factor was carried out. Position refers to the sequence in which drivers encountered the four driving blocks. For example, the first position represents drivers' ratings for system understanding after having experienced the first driving block. Figure 8-6 illustrates the corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014). Mauchly's test indicated that the assumption of sphericity has been violated, $\chi^2(5) = 27.67$, $p < .001$. Therefore, degrees of freedom were corrected using Greenhouse and Geisser (1959) estimates of sphericity ($\varepsilon = .67$). The ANOVA revealed a significant main effect of position, $F(2, 69.91) = 16.21$, $p < .001$, $\eta_p^2 = .32$. Post-hoc tests (Bonferroni-corrected) showed that drivers' perceived system understanding significantly increased from the first to the second position ($p = .001$), the first to the third position ($p < .001$), the first to the forth position ($p < .001$), and the second to the forth position ($p = .055$). This finding supported the third hypothesis. There was neither a significant main effect of FCA system, $F(2, 35) = 0.73$, $p = .490$, $\eta_p^2 = .04$, nor a significant interaction between position and FCA system, $F(4, 69.91) = 1.00$, $p = .413$, $\eta_p^2 = .05$.

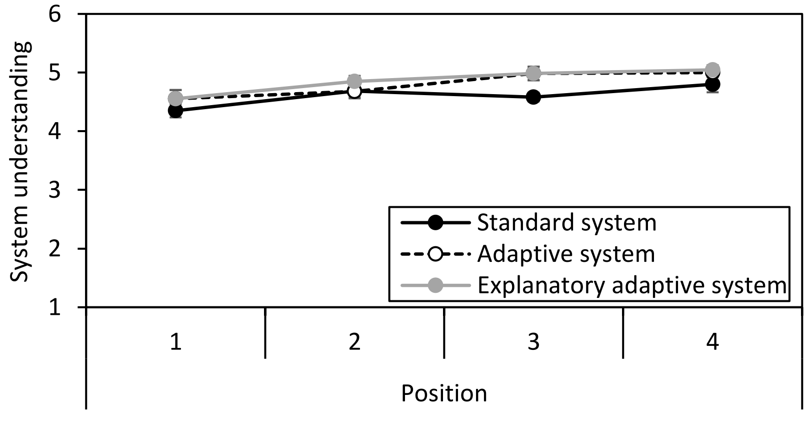

Figure 8-6. Means of system understanding rated after each driving block grouped by FCA system and position of the driving block. Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

8.3.3 System Trust

A one-way ANOVA with FCA system as factor and overall system trust as dependent variable was carried out to test Hypothesis 4 (explanatory adaptive > basic adaptive > standard). Figure 8-7 displays the corresponding means and 95 % confidence intervals. The results showed a significant main effect of FCA system, $F(2, 35) = 4.44$, $p = .019$, $\eta_p^2 = .20$. To specifically address the proposed differences, two unpaired *t*-tests with Bonferroni adjustments were calculated as post-hoc tests. Drivers perceived higher trust in the basic adaptive system than in the standard system on a marginally significant level and with a medium-sized effect, $t(23) = -1.91$, $p = .068$ (one-tailed), $d_{Cohen} = 0.53$. Furthermore, there was no difference between the adaptive and explanatory adaptive system, $t(24) = -0.93$, $p = .363$ (one-tailed), $d_{Cohen} = 0.36$. Therefore, Hypothesis 4 was only partly supported.

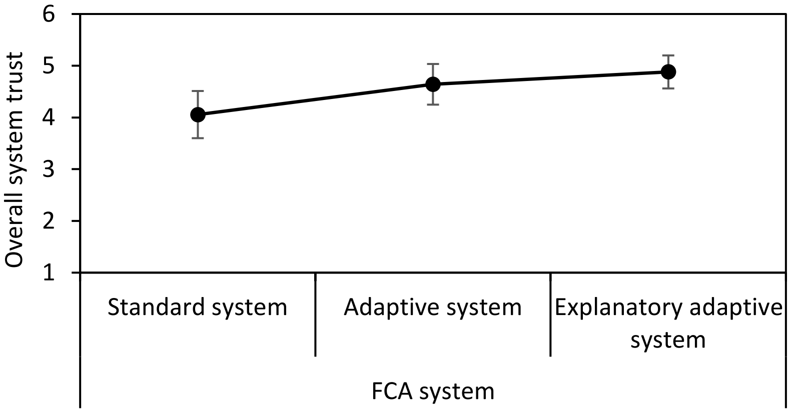

Figure 8-7. Means of overall system trust grouped by FCA system. Error bars display 95 % confidence intervals.

A mixed ANOVA with position as within-subject factor and FCA system as between-subject factor tested the effect of system experience and FCA system on system trust (Hypothesis 5). Position refers to the sequence in which drivers encountered the four driving blocks (see Section 8.3.2). Figure 8-8 shows the corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014). According to the Mauchly's test, the assumption of sphericity has been violated, $\chi^2(5) = 14.17$, $p = .015$. Therefore, degrees of freedom were corrected using Greenhouse and Geisser (1959) estimates of sphericity ($\varepsilon = .84$). The analysis showed significant main effects of position, $F(2.5, 87.96) = 12.21$, $p < .001$, $\eta_p^2 = .26$, and of FCA system, $F(2, 35) = 4.01$, $p = .027$, $\eta_p^2 = .19$. Moreover, there was a marginally significant interaction between position and FCA system, $F(5, 87.96) = 1.96$, $p = .093$, $\eta_p^2 = .10$. To more specifically address the hypothesis, three single repeated-measures ANOVAs for each FCA system were additionally conducted. For the adaptive system, there was a significant main effect of position, *F*(3, 36) = 7.06, *p* = .001, η_p^2 = .37. For the explanatory adaptive system, the analysis also revealed a significant main effect of position, *F*(3, 36) = 7.38, *p* = .001, η_p^2 = .38. Post-hoc tests with Bonferroni adjustment showed that system trust in both systems (marginally) significantly increased from the first to the third position (adaptive *p* = .007, explanatory adaptive *p* = .031) and from the first to the fourth position (adaptive *p* = .074, explanatory adaptive *p* = .008). For the standard system, position had no significant main effect on system trust, *F*(3, 33) = 1.67, *p* = .193, η_p^2 = .13. These findings supported the hypothesis that drivers' system trust in the adaptive systems increased with increasing system experience, while trust in the standard system remained at a constant level.

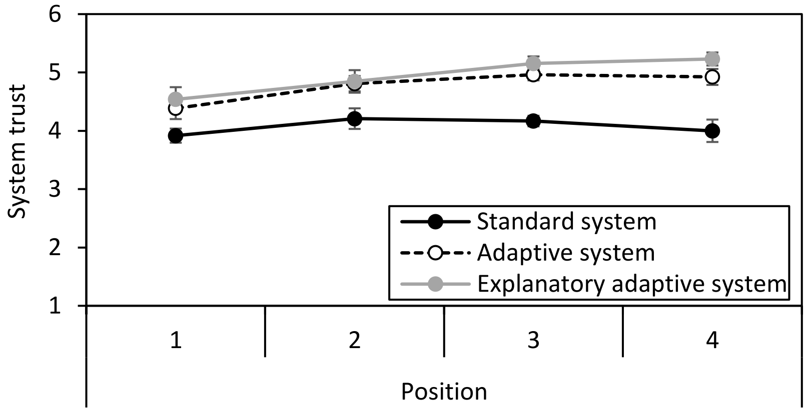

Figure 8-8. Means of system trust rated after each driving block grouped by FCA system and position of the driving block. Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

8.3.4 System Reliability

To test Hypothesis 6 (system reliability: explanatory adaptive > basic adaptive > standard), a one-way ANOVA with FCA system as factor was conducted. Figure 8-9 illustrates the corresponding means and 95 % confidence intervals. There was no significant main effect of FCA system, *F*(2, 35) = 1.12, *p* = .314, η_p^2 = .06. To specifically address the proposed differences, two unpaired *t*-tests with Bonferroni adjustments were calculated as post-hoc tests. Even though drivers did not significantly perceive the adaptive system to be more reliable than the standard system, there was a medium-sized effect, *t*(23) = -1.41, *p* = .173 (one-tailed), d_{Cohen} = 0.56. Additionally, there was no significant difference between the adaptive and explanatory adaptive system, *t*(24) = 0.24, *p* = .811 (one-tailed), d_{Cohen} = 0.1. Overall, these results did not support Hypothesis 6.

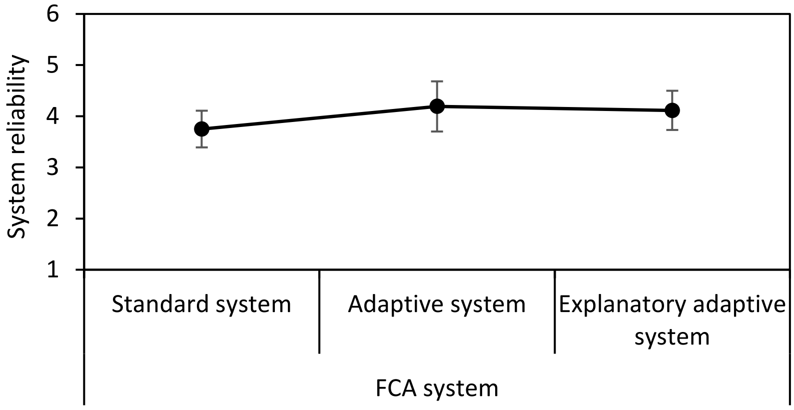

Figure 8-9. Means of system reliability grouped by FCA system. Error bars display 95 % confidence intervals.

8.3.5 System Acceptance

A one-way MANOVA with FCA system as between-subject factor and the scales of the system acceptance questionnaire as dependent variables did not show a multivariate main effect of FCA system, Wilks' λ = .85, $F(8, 64) = 0.68$, $p = .707$, $\eta_p^2 = .08$. Figure 8-10 illustrates the corresponding means and 95 % confidence intervals of all dependent variables. None of the univariate tests revealed a significant main effect of FCA system (Table 8-3). Therefore, no post-hoc tests were conducted to further test Hypothesis 7. Except for behavioural intention, the means supported the hypothesised acceptance ranking of the FCA systems. However, the mean differences were not significant and, thus, Hypothesis 7 had to be rejected.

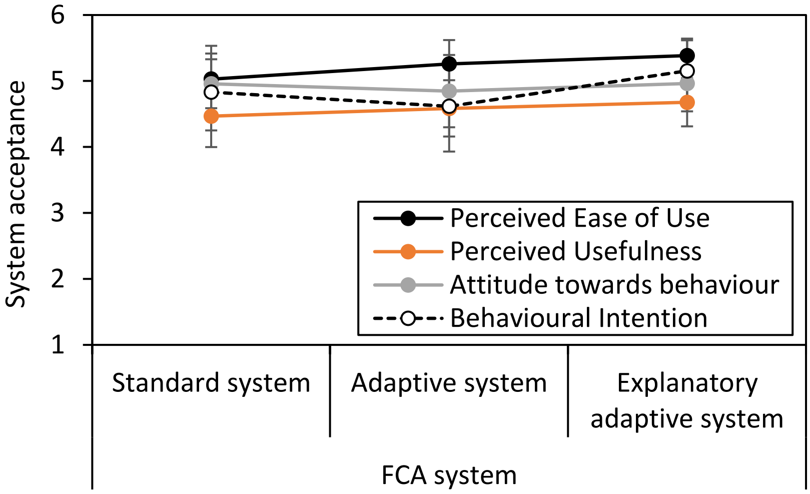

Figure 8-10. Means of system acceptance grouped by FCA system and the scales of the acceptance questionnaire. Error bars display 95 % confidence intervals.

Table 8-3

Univariate Effects of FCA system on Perceived Ease of Use, Perceived Usefulness, Attitude towards Behaviour, and Behavioural Intention

Univariate Effects	***df1***	***df2***	***F***	**η_p^2**
Perceived Ease of Use	2	35	0.87	.05
Perceived Usefulness	2	35	0.24	.01
Attitude towards Behaviour	2	35	0.08	.01
Behavioural Intention	2	35	0.83	.05

Note. Standard system: *n* = 12; adaptive system: *n* = 13; explanatory adaptive system: *n* = 13.
†*p* < .10. **p* < .05. ***p* < .01. ****p* < .001.

8.3.6 Driver Responses to Unnecessary Alarms

The analyses of driver responses to unnecessary alarms and without receiving alarms considered only responses to test events in which drivers' manoeuvre intention did *not* interfere with the encountered traffic event and the potential conflict dissolved. In these situations, the standard system activated an unnecessary FCA, while the adaptive system suppressed the FCA.

To test if drivers' responses to unnecessary alarms decrease as the number of encounters with unnecessary alarms increase (Hypothesis 8), only driver responses to the standard system were considered for data analysis. Two repeated-measures MANOVAs with position as factor and magnitude of speed reduction and maximum deceleration as dependent variables were carried out separately for each traffic scenario, intersection and lead vehicle. The rationale behind conducting two separate analyses was to take potential differences between the two traffic scenarios lead vehicle and intersection into account, while avoiding a further reduction of the sample size for the MANOVAs. As the initial sample sizes for both systems were already quite small (*n* = 12 for standard system, *n* = 13 for adaptive system) and some measurement points had to be excluded from the analyses (see Section 8.2.7), traffic scenario as additional factor would have reduced the overall sample size of the MANOVA. Position refers to the sequence in which drivers encountered the four test events of each traffic scenario. The solid lanes in Figure 8-11 show the corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014) for the group with the standard system in both traffic scenarios.

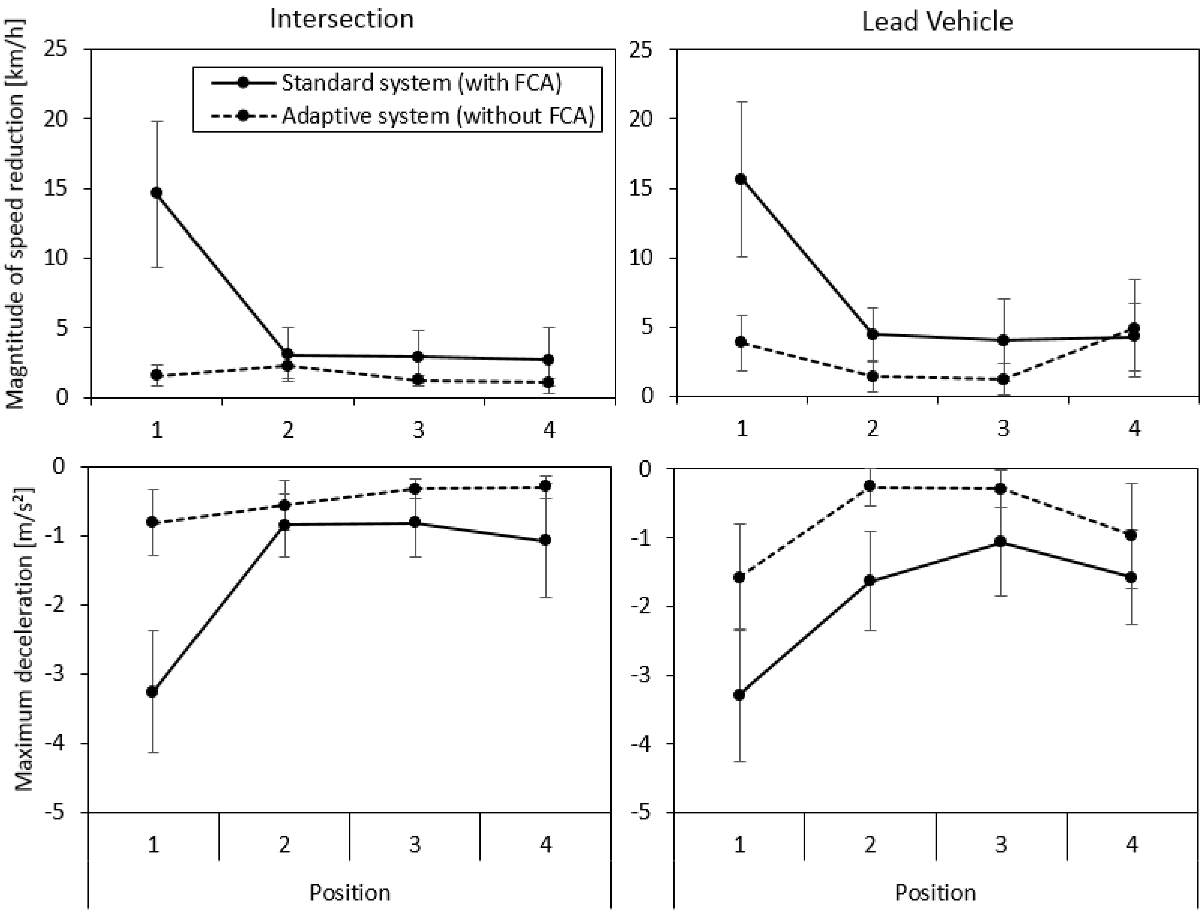

Figure 8-11. Means of magnitude of speed reduction (upper part) and maximum deceleration (lower part) grouped by traffic scenario, position, and FCA system (standard and adaptive). Error bars display within-group standard errors of the means (O'Brien & Cousineau, 2014).

With regard to the *intersection scenario*, the MANOVA (with $N = 9$) revealed a marginally significant multivariate effect of position with a large-sized effect, Wilks' $\lambda = .08$, $F(6, 3) = 5.60$, $p = .093$, $\eta_p^2 = .92$. For both dependent variables, the assumption of sphericity has been violated. For magnitude of speed reduction, the Mauchly's test indicated $\chi^2(5) = 29.29$, $p < .001$. Thus, degrees of freedom were corrected using Greenhouse and Geisser (1959) estimates of sphericity ($\varepsilon = .41$). Based on another significant Mauchly's test, $\chi^2(5) = 27.64$, $p < .001$, degrees of freedom for maximum deceleration were corrected with $\varepsilon = .66$. There were significant univariate main effects of position on magnitude of speed reduction, $F(1.23, 9.80) = 6.75$, $p = .023$, $\eta_p^2 = .46$, and on maximum deceleration, $F(1.99, 15.89) = 5.88$, $p = .012$, $\eta_p^2 = .42$. For magnitude of speed reduction, post-hoc tests with Bonferroni correction did not reveal significant pairwise differences. For maximum deceleration, post-hoc tests with Bonferroni correction showed marginally significant differences between Position 1 and 2 ($p = .072$) and between Position 1 and 3 ($p = .064$).

The second MANOVA for the *lead vehicle scenario* ($N = 11$) did not show a significant multivariate effect of position, Wilks' $\lambda = .37$, $F(6, 5) = 1.44$, $p = .352$, $\eta_p^2 = .63$. However, the effect size was large. Mauchly's test indicated that the assumption of sphericity has been violated for magnitude of speed reduction, $\chi^2(5) = 21.15$, $p = .001$. Therefore, degrees of freedom were corrected using Greenhouse and Geisser (1959) estimates of sphericity ($\varepsilon = .44$). The MANOVA revealed significant univariate main effects of position on magnitude of speed reduction, $F(1.31, 13.12) = 5.22$, $p = .032$, $\eta_p^2 = .34$, and on maximum deceleration, $F(3, 30) = 2.93$, $p = .049$, $\eta_p^2 = .23$. Post-hoc tests with Bonferroni correction did not show significant pairwise differences for both dependent variables. Overall, the significant univariate main effects of position in combination with the descriptive data (solid lanes in Figure 8-11) supported Hypothesis 8.

To test if the difference in driver behaviour in response to unnecessary alarms and without receiving alarms became less pronounced with multiple exposures to traffic situations in which their manoeuvre intention caused a dissolving outcome (Hypothesis 9), only responses to the standard system and the adaptive systems were relevant. Two mixed MANOVAs with position as within-subject factor, FCA system as between-subject factor, and magnitude of speed reduction and maximum deceleration as dependent variables were carried out separately for each traffic scenario, intersection and lead vehicle. The explanations for conducting two separate analyses are similar to those described in the previous paragraph. Table 8-4 reports the test statistics of the multivariate and univariate tests of the intersection scenario and Table 8-5 those of the lead vehicle scenario. Figure 8-11 illustrates the corresponding means and within-group standard errors of the means (O'Brien & Cousineau, 2014) of both traffic scenarios. The MANOVAs for both scenarios revealed significant univariate main effects of FCA system on magnitude of speed reduction and maximum deceleration. Drivers reduced their speed to a higher extent and decelerated more strongly in response to unnecessary alarms than without alarms. In both traffic scenarios, there were (marginally) significant univariate interaction effects between position and FCA system (except for maximum deceleration in the lead vehicle scenario). As illustrated in Figure 8-11, the development of driver responses with increasing experience differed dependent on the FCA system. During the first encounter of the intersection or the lead vehicle scenario, drivers who received unnecessary alarms (standard system) reduced their speed to a higher extent and decelerated more strongly than drivers without alarms (adaptive system). Based on the descriptive data, the difference in driver behaviour in response to unnecessary alarms and without alarms already became less pronounced at the second encounter. To the subsequent encounters of the test events, drivers with both FCA systems showed responses of equal intensity. Overall, responses of drivers with the adaptive system remained stable independent of the position of the traffic events. One exception was that drivers without alarms decelerated more strongly the first time they encountered the lead vehicle scenario than the second and following times (lower right part of Figure 8-11). Overall, the results supported Hypothesis 9.

Table 8-4

Results of MANOVA for the Intersection Scenario with Multivariate and Univariate Effects of Position and FCA System on Magnitude of Speed Reduction and Maximum Deceleration

	df1	***df2***	**Wilks' λ**	***F***	**η_p^2**
Multivariate effects					
Position	6	10	.29	4.07*	.71
FCA System	2	14	.66	3.64†	.34
Position* FCA System	6	10	.66	0.94	.36
Univariate effects					
Magnitude of speed reduction					
Position	1.26	18.89		5.90*	.28
FCA System	1	15		7.68*	.34
Position* FCA System	1.26	18.89		5.76*	.28
Maximum deceleration					
Position	2.03	30.47		6.19**	.29
FCA System	1	15		5.90*	.28
Position* FCA System	2.03	30.47		3.11†	.17

Note. Standard system: *n* = 9; Adaptive system: *n* = 8. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity, $\varepsilon = .42$ for magnitude of speed reduction and $\varepsilon = .68$ for maximum deceleration. †$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

Table 8-5

Results of MANOVA for the Lead Vehicle Scenario with Multivariate and Univariate Effects of Position and FCA System on Magnitude of Speed Reduction and Maximum Deceleration

	df1	***df2***	**Wilks' λ**	***F***	**η_p^2**
Multivariate effects					
Position	6	16	.61	1.69	.39
FCA System	2	20	.82	2.26	.18
Position* FCA System	6	16	.57	1.99	.43
Univariate effects					
Magnitude of speed reduction					
Position	1.78	37.44		5.27*	.20
FCA System	1	21		4.44*	.18
Position* FCA System	1.78	37.44		3.38*	.14
Maximum deceleration					
Position	2.22	46.56		5.06**	.19
FCA System	1	21		4.71*	.18
Position* FCA System	2.22	46.56		0.55	.03

Note. Standard system: *n* = 11; Adaptive system: *n* = 12. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity, *ε* = .59 for magnitude of speed reduction and *ε* = .74 for maximum deceleration. †*p* < .10. **p* < .05. ***p* < .01. ****p* < .001.

8.4 Discussion

The main goal of Study 4 was to compare drivers' subjective evaluations of two adaptive FCA systems that used manoeuvre intention as adaption parameter to those of a conventional FCA system. While one adaptive system completely suppressed unnecessary alarms, the other adaptive system did not only suppress unnecessary alarms, but also provided an explanation to the drivers. Moreover, the study sought to gain insights into the development of drivers' responses to unnecessary alarms with multiple exposures to similar traffic situations.

With regard to drivers' perceived system understanding and their mental models of the adopted activation strategies, the results did not reveal differences between the FCA systems. The descriptive data suggested that drivers perceived both adaptive systems as more understandable than the standard system. Furthermore, there were no differences between the adaptive system and the explanatory adaptive system with regard to perceived system understanding and the quality of the mental models. These findings contradicted the hypothesis that drivers would have more difficulties to understand the functioning of basic adaptive system than that of the standard system and the explanatory adaptive system. Thus, in contrast to the theoretical considerations by Smith et al. (2008), the adaptive systems did not seem to have interfered with the development of a correct mental model. Drivers were able to understand the significance of manoeuvre intention for the system's alarm activation strategy, even without explicit explanation. This conclusion was also supported by the fact that most drivers of both adaptive systems were able to identify manoeuvre intention as adaption parameter. To sum up, manoeuvre intention seemed to be a comprehensible adaption parameter. As long as an adaptive system uses only one understandable adaption parameter and the adaption works perfectly reliable, drivers do not seem to need an explicit explanation for alarm suppression. Moreover, the results revealed that drivers went through a learning process which increased their perceived system understanding with increasing system experience. Independent of the used FCA system and its activation strategy, multiple encounters with situations that either led to an alarm activation or suppression helped drivers to comprehend how the FCA system works. When interpreting the results, it must be considered that the development of perceived system understanding and the identification of the adaption parameter might have been easier and took a shorter period of time in the present study than under real traffic conditions. In the study, drivers experienced each of the two traffic scenarios eight times (with different environments) within a short time frame of 1 – 1.5 hours. In real traffic, it would take a longer period of time to experience an equal amount of situations in which FCAs are either activated or suppressed. Additionally, use cases for alarm activation or suppression would vary to a higher degree than in the present study where similar traffic scenarios were repeatedly encountered with different environments.

Furthermore, the study provided insights into drivers' trust in the adaptive systems. In line with the hypothesis, there was a tendency that drivers perceived higher trust in the basic adaptive system than in the standard system. However, the result that drivers did not trust more in the adaptive system with explanation for alarm suppression than in the basic adaptive system contradicted the hypothesis. It is assumed that perceived system understanding might serve as a basis for system trust. Therefore, as drivers perceived a higher understanding of the basic adaptive system than initially expected, both adaptive systems with and without explanation resulted in a similar level of perceived system trust. Future research could examine the relationship between these two variables. Additionally, system trust in both adaptive systems increased with increasing system experience, while trust in the standard system remained at a constant level. With multiple exposures to similar traffic events, drivers learned that the adaptive systems suppressed FCAs in a consistent manner. The insights gained from this learning process might have caused an increase in system trust over time. Even if users of the standard system were able to understand its activation strategy, regularly issued unnecessary alarms conceivably counteracted an increase of system trust. Future research should investigate the further development of trust in a non-adaptive system that regularly activates unnecessary alarms. It would be interesting to examine if system trust would remain at this constant and tolerably high level or if it would start to decrease at a certain point.

System reliability did not differ between the FCA systems. Even though the descriptive data suggested that drivers perceived both adaptive systems to be more reliable than the standard system, the differences between the FCA systems did not reach statistical significance. Drivers might have perceived the standard system as rather reliable because it was able to reliably detect all situations with high collision risk. This ability of the standard system might have served as a basis for perceived system reliability and was, finally, more important than the ability to suppress unnecessary alarms. Moreover, contrary to the hypothesis, drivers perceived both adaptive systems as equally reliable. This finding could be explained by the fact that drivers' perceived system understanding was equally high for both systems. Additionally, their mental models for the applied adaption strategy had a similar quality. The knowledge that the basic adaptive system intentionally suppressed certain alarms rather than missed to detect hazardous situations might have led to a perceived reliability as high as that of the explanatory adaptive system.

The study found no differences in the overall acceptance of the different FCA systems. However, even if the differences of the acceptance ratings did not reach statistical significance, the means generally supported the hypothesis that drivers indicated the highest acceptance for the explanatory adaptive system, followed by the basic adaptive system, while the standard system received the lowest evaluation. Social desirability might have influenced drivers' acceptance ratings. Participants were not informed of how their FCA system differed to the other FCA systems tested in the study. They conceivably had their own hypotheses about the purpose of the study. As participants generally know that simulator studies at WIVW GmbH are usually conducted on behalf of a car manufacturer, they might have aimed to answer to the acceptance items in a favourable way. This might have masked potential differences between the standard system and the adaptive systems. Furthermore, the between-subject design for FCA system could have mitigated differences between the systems. There were several reasons for the decision to vary this factor between participants, e.g. learning effects of the test events and the total duration of the study per participant. However, there might have been clearer differences between the acceptance ratings if FCA system had been a within-subject factor and drivers had been able to compare the different FCA systems. However, there were differences between the FCA systems concerning system trust despite the between-subjects design. Moreover, as mean system acceptance was relatively high for all FCA systems, it is not assumed that a within-subject design would have fundamentally reduced the acceptance ratings of the standard system.

With regard to the development of drivers' responses to unnecessary alarms with increasing system experience, the findings supported both hypotheses. In response to the first unnecessary alarm in the intersection scenario and in the lead vehicle scenario, drivers reacted with moderate decelerations and speed reductions. In contrast, drivers who showed their natural driving behaviour without receiving an FCA did not or only minimally react to these first events. Already at the second encounter with each traffic scenario, drivers reduced the intensity of their responses to unnecessary alarms. The responses almost approached the level of those of the drivers without FCAs. At the third and fourth encounter, drivers' responses to unnecessary alarms remained constantly low. The results were in line with the findings of the naturalistic driving studies by Flannagan et al. (2016) and General Motors Corporation (2005) and demonstrated that drivers' responsiveness to unnecessary alarms decreased with increasing system experience. Additionally, the difference in driver behaviour in response to unnecessary alarms and without receiving alarms became less pronounced with increasing system experience. After having experienced only one event of each traffic scenario that activated an unnecessary alarm, drivers with the standard system conceivably developed a schema that allowed them to identify traffic constellations that previously activated an unnecessary alarm. When they experienced the same situation a second, third, or fourth time, they were able to use this schema. It helped them to anticipate that the other road user could potentially trigger an unnecessary alarm even though it would not constitute a hazard. Therefore, in the naturalistic driving studies, alarm rates decreased over time in the scenarios where the ego and the lead vehicle did not remain in the same lane after the FCA was issued. Under real traffic conditions, drivers were able to use their schemata to adjust their behaviour in order to avoid setting off an unnecessary alarm, while drivers in the present study could not avoid these situations. It must be considered that the development of schemata would be presumably more difficult and would require more time in real traffic than in the present study. Here, only the environments around the basic traffic scenarios varied between the test events. Therefore, the transfer of a schema to another event was facilitated. However, under real traffic conditions, there are more variables that dynamically change from one use case to another. The transfer of learned schemata to new traffic scenarios is assumed to be more difficult. Thus, the choice of the most appropriate schema in order to anticipate unnecessary alarms and to cross-check the validity of an unnecessary alarm would require more cognitive resources than in the present study. Moreover, real traffic conditions usually lead to far fewer unnecessary alarms within a short period of time which additionally impedes the development of adequate schemata. Future research could investigate the development of drivers' responses to unnecessary alarms under real traffic conditions. If drivers were able to develop appropriate schemata within a quite short period of time that help them to not or only minimally respond to unnecessary alarms, unnecessary alarms would not be very critical from a safety perspective.

8.5 Conclusion

First, Study 4 provided insights into the evaluation of an adaptive FCA system that used manoeuvre intention as adaption parameter. Second, the study investigated the development of drivers' responses to unnecessary alarms with increasing system experience. The system was compared to a similar adaptive system that additionally gave an explanation for alarm suppression and a conventional FCA system that activated unnecessary alarms. Drivers had no difficulties to understand the adaption strategy of the adaptive system and to develop a correct mental model, even without explanation. Hence, manoeuvre intention seemed to be a comprehensible adaption parameter for a negative adaption strategy. In the course of the simulation drive, perceived system understanding of all FCA systems increased. Moreover, drivers' trust in the adaptive systems was higher than in the standard system. While trust in both adaptive systems increased with increasing system experience, trust in the standard system remained at a constant level. Even if the means of system reliability and acceptance pointed in the hypothesised direction, the differences were not statistically relevant. To sum up, the development of system understanding and system trust seems to represent a learning process that might, finally, influence drivers' estimation of system trust, reliability, and acceptance.

The study found that drivers' responsiveness to unnecessary alarms in situations with predictable dissolving outcome decreased as the number of encounters with unnecessary alarms increased. When comparing responses to unnecessary alarms to driving behaviour in the same situations without alarms, the behavioural differences became less pronounced with repeated exposure to similar traffic scenarios that typically activate unnecessary alarms. After having received the first unnecessary alarm in each traffic scenario that initially provoked decelerations and speed reductions of medium intensity, drivers only minimally responded to the subsequently activated unnecessary alarms. At least in a controlled driving simulator context, drivers seem to be able to develop schemata that allow them to identify situations that potentially trigger unnecessary alarms and to avoid unnecessarily intensive alarm responses.

9 General Discussion

The alarm activation of conventional FCA systems depends on physical measurements. Such an activation strategy regularly sets off alarms that drivers subjectively perceive as unnecessary (see Section 2.3.2). Although previous research on adaptive alarm systems sought to reduce the rate of unnecessary alarms, there was a lack of knowledge about factors that determine drivers' need for assistance (see Section 2.4). Moreover, no previous study has systematically investigated the impact of unnecessary alarms on drivers' subjective evaluations and alarm responses (see Sections 2.3.4 and 2.3.5).

The main objective of this thesis was to investigate which psychological factors and processes have an impact on drivers' perceived need for assistance in potential collision situations to understand under which conditions drivers perceive collision alarms as unnecessary. Therefore, a theoretical framework of drivers' subjective alarm evaluation was developed that served as a basis to derive related hypotheses (Section 3.1, Figure 9-1). An additional goal of this thesis was to elucidate the impact of unnecessary alarms on drivers' acceptance and alarm responses.

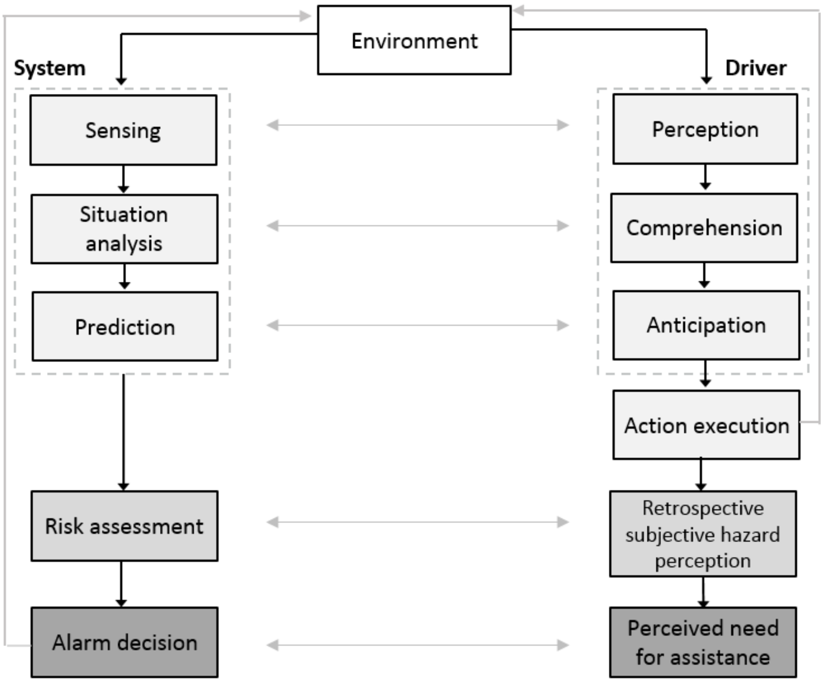

Figure 9-1. Theoretical framework of drivers' subjective alarm evaluation.

To address the research questions (see Section 3.2), four driving simulator studies were conducted (see Chapters 5, 6, 7, and 8). In all studies, participants encountered situations with identical physical conditions between their own vehicle and another road user (TTC values) that would usually activate FCAs, while the outcome of the potential conflict was varied. The conflict either remained or dissolved within the next few seconds. The outcome was dependent on drivers' own manoeuvre intentions (manipulated by navigation instructions to the participant) or intentions attributed other road users (manipulated by environmental cues). This method allowed to create situations that would lead to constantly high risk assessments of the alarm system, while drivers' retrospective subjective hazard perception, perceived need for assistance, alarm acceptance, and alarm responses were assumed to differ dependent on their anticipations of the situation outcome.

The following sections summarise and discuss the main findings of the conducted driving simulator studies in relation to the hypotheses and research questions derived from the theoretical framework of drivers' subjective alarm evaluation (Chapter 3, Figure 9-1). Based on the results, indications for the validity of the proposed theoretical framework are derived. Moreover, the insights into the impact of unnecessary alarms on drivers' acceptance and alarm responses are summarised and discussed. In addition, limitations, need for future research, and practical implications of the findings of this thesis will be elucidated.

9.1 Drivers' Perceived Need for Assistance in Potential Collision Situations

The results of this thesis provided evidence for the hypotheses derived from the theoretical framework of drivers' subjective alarm evaluation (see Chapter 3). Taken together, the results revealed that situations which would cause a constantly high level of system risk assessment due to identical TTC values can result in varying levels of human subjective hazard perception. This discrepancy can be caused by an advantage of the driver over the system in anticipating the outcome of a complex driving situation. While the system's prediction based on physical measurements is only valid if the potential conflict remains in the further course, drivers' anticipation additionally considers their own manoeuvre intentions and those attributed to other road users. Given a dissolving conflict that was predictable for the driver, system risk assessment exceeds drivers' subjective hazard perception. Consequently, drivers perceive a low need for assistance and evaluate alarms activated by the FCA system as unnecessary. Figure 9-2 illustrates the described factors and processes that lead to alarms which drivers perceive as unnecessary. The following sections summarise and discuss the main conclusions concerning drivers' perceived need for assistance drawn from the results of this thesis in more detail.

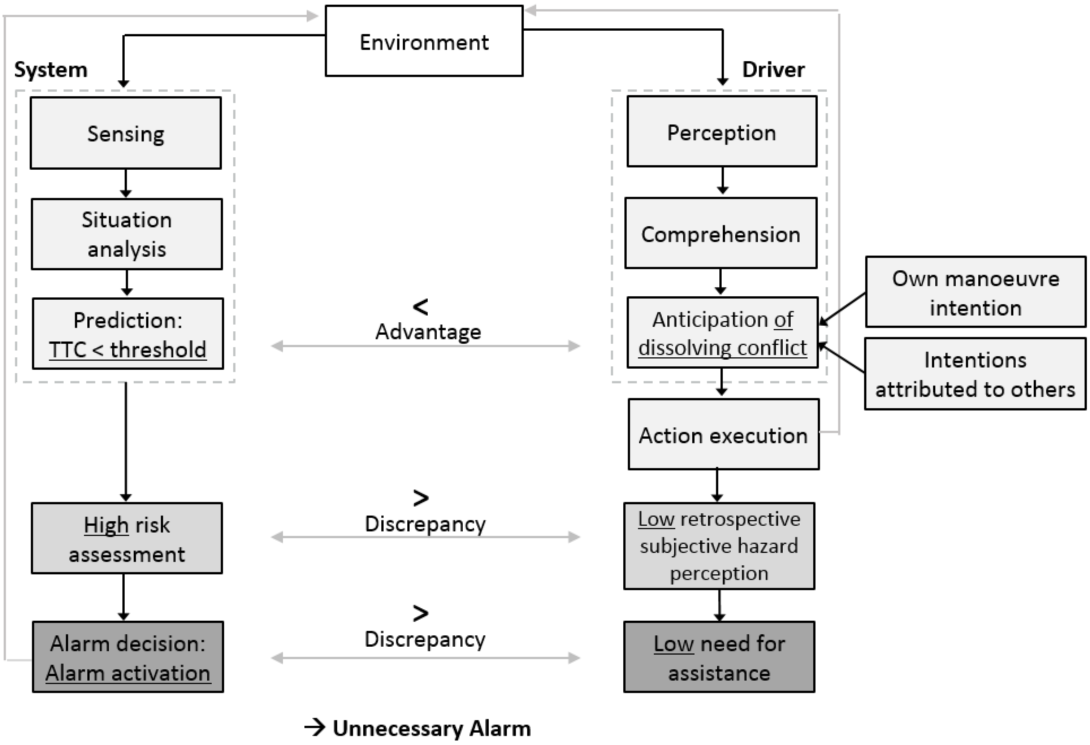

Figure 9-2. Emergence of unnecessary alarms based on the theoretical framework and on the results of the empirical research conducted in this thesis.

9.1.1 Retrospective Subjective Hazard Perception

The first hypothesis derived from the theoretical framework proposed that drivers' subjective hazard perception predict their perceived need for assistance (see Section 3.1; lower right part of Figure 9-1). The results of Study 1 and 2 supported this hypothesis. Drivers' subjective hazard perception either measured during (Study 1) or after the encountered traffic event (Study 2) mediated the effect of system risk assessment on drivers' perceived need for assistance. Hence, drivers' subjective hazard perception regarding the encountered traffic situation was the central factor that influenced their perceived need for assistance. Additionally, even though Study 3 did not explicitly test this relationship, it demonstrated that lead vehicle behaviour and its predictability had the same impact on subjective hazard perception as on perceived need for assistance. Drivers perceived situations with unpredictable outcome as more hazardous than situations with predictable outcome and, thus, also perceived a higher need for assistance. Prior research showed that the subjective hazard perception of a product positively influenced the perceived necessity of static product warnings (Laughery & Wogalter, 2006; Wogalter et al., 1991). The present research extended these findings and revealed that subjective hazard perception also determines the perceived need for *dynamic* alarms. The assumption that subjective hazard perception would also influence the perceived need for alarms provided by driver assistance systems was derived from results of surveys and interviews (Eichelberger & McCartt, 2014; LeBlanc et al., 2006b; Portouli et al., 2006; van Driel & van Arem, 2005). This thesis supports this assumption based on systematic experimental investigations.

The gained knowledge about the impact of drivers' retrospective subjective hazard perception on their perceived need for assistance provides a first orientation for the understanding of drivers' actual need for assistance. The finding implies that drivers perceive those alarms as unnecessary that are activated in situations which they perceive as little hazardous and, thus, result in a low perceived need for assistance. In turn, drivers evaluate alarms as useful when they perceived the encountered situation as hazardous and, therefore, perceived a higher need for assistance. Prior research has usually taken into account only one single isolated adaption parameter to predict need for assistance, e.g. visual attention (e.g. Hammoud et al., 2008; Trefflich, 2010) or mental workload (Reinmueller et al., 2018). Based on the present results, the consideration of only one adaption parameter seems to be insufficient and might not appropriately represent drivers' need for assistance. For example, despite being visually and/or cognitively attentive, a driver might perceive a highly demanding and time-critical situation as hazardous. In this case, the driver would perceive an increased need for assistance and would evaluate an issued alarm as useful. Drivers' subjective hazard perception and, accordingly, their perceived need for assistance is conceivably predicted by an interaction of several factors. This thesis provided evidence on relevant human factors that influence drivers' subjective hazard perception and perceived need for assistance. The corresponding findings are discussed in the following section.

9.1.2 The Emergence of Discrepancies between Human Subjective Hazard Perception and System Risk Assessment

The second hypothesis derived from the theoretical framework of drivers' subjective alarm evaluation proposed that drivers perceive alarms as unnecessary which are activated in situations that simultaneously result in a high system risk assessment and a low retrospective subjective hazard perception (see Section 3.1). The findings of Study 1, 2, and 3 supported this hypothesis. It was shown that situations which would cause a constantly high level of system risk assessment due to identical TTC values resulted in varying levels of human subjective hazard perception. Based on the identified impact of subjective hazard perception on perceived need for assistance (see Section 9.1.1) in combination with the impact of system risk assessment on alarm decision, the FCA system would activate an alarm while the driver perceives a low need for assistance. In such situations, drivers perceive alarms as unnecessary. The following sections address the results of this thesis that provided evidence on how such a discrepancy can arise.

Based on the theoretical framework of drivers' subjective alarm evaluation, it was hypothesised that a discrepancy between system risk assessment and human subjective hazard perception results from an advantage of the driver of the system in anticipating the outcome of a potential conflict (Hypothesis III in Section 3.1.3). It was assumed that human drivers consider additional factors for their anticipation compared to the alarm system. More specifically, the proposed factors were drivers' own manoeuvre intentions (Hypothesis IIIa in Section 3.1.3) and those attributed to other road users (Hypothesis IIIb in Section 3.1.3).

9.1.2.1 Drivers' Manoeuvre Intention

The results of Studies 1 and 2 largely corroborated the hypothesis that drivers have an advantage over the system as they consider their own manoeuvre intentions to anticipate the outcome of a potential conflict (Hypothesis IIIa in Section 3.1.3). In most of the examined scenarios, drivers perceived events with high system risk assessment (based on low TTC value) as subjectively more hazardous when the critical traffic event interfered with their current manoeuvre intention (conflict remained) than without interference between traffic event and manoeuvre intention (conflict dissolved). When drivers anticipated a dissolving outcome of a potential conflict dependent on their current manoeuvre intention, their subjective hazard perception was lower than the system's risk assessment resulting in a discrepancy. Based on the mediated relationship between system risk assessment and perceived need for assistance via subjective hazard perception (see Section 9.1.1), the findings imply that drivers also perceive a lower need for assistance under these conditions.

Beyond perceived need for assistance, Studies 2 and 4 investigated the impact of manoeuvre intention on drivers' explicit usefulness evaluation of received alarms. In Study 2, the results of the "turn right" scenario (left panel of Figure 6-2) revealed that most drivers classified received alarms as unnecessary when their current manoeuvre intention caused a dissolving conflict and as useful when the conflict remained (see Section 6.3.4). In this scenario, drivers also indicated a lower acceptance for alarms predefined as unnecessary (dissolving conflict) than for alarms predefined as useful (remaining conflict). In the “turn left” scenario (right panel of Figure 6-2), however, drivers’ classification of alarms as unnecessary or useful could not be clearly assigned to their current manoeuvre intention. Accordingly, their acceptance for alarms predefined as unnecessary or useful did also not differ. Possible explanations can be found in the following paragraph. Study 4 provided clearer findings concerning drivers’ perceived alarm usefulness dependent on their manoeuvre intention. On average, drivers disagreed that received FCAs were useful when their current manoeuvre intention caused a dissolving conflict. Based on this finding, a low level of perceived need for assistance expresses that drivers perceive a received alarm as unnecessary. Similarly, drivers agreed that FCAs were useful when the conflict remained due to their manoeuvre intention. Thus, a high level of perceived need for assistance implies that a received alarm is evaluated as useful.

It must be considered that the impact of manoeuvre intention was not consistent in all tested scenarios. In both braking lead vehicle scenarios in Study 1 (“turn right” and “turn left”, Figure 6-2) and the “turn left” scenario in Study 2 (right panel of Figure 6-2), drivers perceived the braking lead vehicle as equally hazardous independent of their manoeuvre intention (see Section 6.3.1). However, Studies 2 and 4 revealed a clear impact of manoeuvre intention on drivers’ subjective hazard perception, perceived need for assistance, alarm usefulness, and acceptance for the “turn right” scenario (left panel of Figure 6-2). Thus, it is assumed that the method of blanking the screen in Study 1 might have caused a misjudgement of the magnitude of deceleration of the braking lead vehicle in situations with low system risk assessment and, thus, mitigated the moderating effect of manoeuvre intention. A detailed explanation for this assumption can be found in Section 5.4. Nevertheless, in the “turn left” scenario (right panel of Figure 6-2), manoeuvre intention neither had an effect in Study 1, nor in Study 2. As already discussed in Section 6.4 in more detail, this finding could be explained as follows. Low TTC values were always forced by another road user in a time-critical manner. Thus, drivers’ advantage over the system in anticipating a dissolving outcome of a conflict became relevant just a maximum of two seconds before a potential crash could have happened. If drivers themselves had provoked such a traffic constellation, they would have been able to consider their manoeuvre intention earlier. Under this condition, manoeuvre intention might have influenced subjective hazard perception, perceived need for assistance, and alarm acceptance. However, this assumption remains to be tested. The combination of this methodological limitation and the lack of perceived spatial separation in the “turn left” scenario (see also Section 6.4) is assumed to be the most probable explanation for the deviating results in this scenario.

9.1.2.2 Intentions Attributed to Other Road Users

In line with Hypothesis IIIb (see Section 3.1.3), Study 3 revealed that drivers’ ability to anticipate subsequent actions of other road users represents a further advantage of the driver over the system. Dependent on drivers’ ability to anticipate the other’s subsequent actions and the outcome of the conflict, potential conflicts with identical TTC values resulted in varying levels of human subjective hazard perception. Drivers perceived the situation as less hazardous in retrospect when they were able to anticipate that the conflict will finally dissolve than if this possibility was not given due to sight obstructions. The results suggested that drivers were able to infer intentions of other road users from the context in which the actions were embedded. They understood the significance of certain environmental cues by using schemata stored in long-term memory that were developed by prior experiences with similar situations (Stahl, 2015; Zunino et al., 2017). This ability allowed for anticipations of the outcome of the potential conflict and, therefore, for more differentiated subjective hazard perceptions than the system’s risk assessment exclusively based on TTC values. In all conditions, drivers’ perceived need for assistance was equally pronounced as their subjective hazard perception. According to the results, system risk assessment deviates from drivers’ subjective hazard perception under certain conditions. Such a discrepancy is most pronounced when the human driver is able to anticipate a dissolving outcome of the conflict. In contrast, system risk assessment and drivers’ subjective hazard perception approach each other when neither the system nor the driver are able to anticipate that the potential conflict would finally remain.

Drivers indicated a lower acceptance for alarms issued when the lead vehicle left the lane than for alarms activated when the conflict remained as the lead vehicle stayed in the lane. In addition, drivers’ ability to anticipate that the lead vehicle intends to leave the lane and the conflict will dissolve had an impact on their acceptance of unnecessary alarms. They evaluated unnecessary alarms as less acceptable when they were able to anticipate the subsequent action of the lead vehicle than if not. This result suggests that drivers might perceive unnecessary alarms as more pardonable when neither they themselves nor the system could anticipate that the conflict will finally dissolve and the alarm would be unnecessary. This finding might offer an explanation for relatively positive subjective evaluations of unnecessary alarms in the study by Naujoks et al. (2016) (see Section 2.3.5). In their study, drivers were not able to anticipate that the encountered potential conflict would finally dissolve.

9.2 Driver Responses to Unnecessary Alarms

This thesis aimed to provide knowledge about drivers' responses to unnecessary alarms. Studies 2, 3, and 4 addressed this research question. It was assumed that previous experiences with unnecessary alarms and drivers' ability to anticipate a dissolving outcome of the potential conflict might influence the intensity of braking responses to unnecessary alarms. In all relevant studies, driver responses to unnecessary alarms were compared to driving behaviour in the same situations without receiving an alarm.

In the short term, without prior experiences with similar situations that activated unnecessary alarms, these alarms resulted in driver responses of moderate intensity. The results of Studies 2 and 3 revealed that drivers who received unnecessary FCAs in situations with predictable dissolving outcome showed stronger braking reactions than drivers who experienced the same situation without FCAs. On average, drivers responded to unnecessary alarms under these conditions with maximum decelerations of -5.61 m/s² (*SD* = 2.09) and speed reductions of 26.84 km/h (*SD* = 11.18). The responses were more intense when drivers' anticipation of a dissolving conflict was based on intentions attributed to other road users (Study 3) than on their own manoeuvre intentions (Study 2). This finding may be explained by the fact that drivers were more confident about their own manoeuvre intentions than about those attributed to other road users. Drivers conceivably considered the estimated reliability of their current anticipations for their action selection. Without being warned, drivers showed only minimal reactions to the encountered situations. This result demonstrates that the dissolving outcome of the situations seemed to be predictable for drivers in both studies. To investigate if the ability to anticipate a dissolving outcome of the conflict influences the intensity of driver responses to unnecessary alarms, drivers in Study 3 additionally encountered situations with an *unpredictable* dissolving outcome. Independent of receiving an unnecessary alarm or not, driver reactions did not differ in situations with predictable and unpredictable dissolving outcomes. It is assumed that this result was associated with drivers' ability to dynamically adjust their situation awareness and actions (Endsley, 1988). Nevertheless, although there were no differences in driving behaviour, drivers perceived situations with unpredictable dissolving outcome as more hazardous and indicated a higher need for assistance than when they were able to anticipate the outcome of the conflict.

The results of Study 4 showed that the intensity of driver responses to unnecessary alarms decreased with multiple exposures to unnecessary alarms. Participants encountered four events of each traffic scenario that varied only with regard to the environmental surrounding. In response to the first experienced unnecessary alarm in each traffic scenario, drivers reacted with moderate decelerations and speed reductions. These responses were of similar intensity as those in Study 2. Already at the second encounter with each traffic scenario, driver responses to unnecessary alarms decreased and approached almost the intensity of driver responses without FCAs. From then on, their alarm responses remained at a constant level. Consequently, by adapting their response criterion β, drivers increased the rate of correct omissions and, at the same time, decreased the rate of commission errors (see Sections 2.3.1 and 2.3.3). In comparison, drivers who did not receive unnecessary FCAs reacted only minimally from the first encounter on. Previous driving simulator studies (Lees & Lee, 2007; Zarife, 2014) and naturalistic driving studies (Flannagan et al., 2016; General Motors Corporation, 2005) provided inconsistent results regarding the impact of unnecessary alarms on driver responses. The findings of this thesis offer an explanation for the relatively high braking response rates to unnecessary alarms with moderate speed reductions in the driving simulator studies by Lees and Lee (2007) and Zarife (2014) on the one hand and the low braking response rates and minimal decelerations in the naturalistic driving studies by Flannagan et al. (2016) and General Motors Corporation (2005) on the other hand. While the results of the simulator studies represent short-term effects of unnecessary alarms on driver responses, the results of the naturalistic driving studies represent rather long-term effects. The findings can be explained as follows. As unnecessary alarms are usually activated by an apparent trigger, drivers need to invest cognitive resources to comprehend and anticipate if this alarm trigger still constitutes a hazard within the next few seconds. In the short term and without prior experience with situations that usually activate unnecessary alarms, the process of cross-checking the validity of an unnecessary alarm requires cognitive resources and is, therefore, demanding (Gérard & Manzey, 2010). Hence, an FCA initially triggers moderate braking responses as automated stimulus reaction patterns (see Section 2.1.1). This skill-based behaviour (Rasmussen, 1983) does not require much cognitive resources and appears to have a lower probability of a negative outcome than not responding to the alarm and taking the risk of a missing response.

With long-term or increasing system experience, drivers regularly experience unnecessary alarms and learn action-effect relations associated with these special traffic constellations (ideomotor theory; see Section 2.1.2.4; e.g. Hoffmann, 2009). In addition, they are able to develop a schema consisting of traffic constellations that typically activate unnecessary alarms. Drivers might have perceived the action effects during the first encounter(s) as too intense. The next time they encounter such a situation, they can use the knowledge stored in the schema to identify the situation. This knowledge enables drivers to anticipate the activation of an unnecessary alarm or to cross-check its validity when already activated. This process requires less cognitive resources. Drivers have a mental representation of the related action effects and reduce their alarm response in anticipation of a more pleasant sensory effect. During this learning process, drivers learn to select a less intense alarm response or to completely ignore the alarm. Alternatively, drivers might adjust their behaviour to avoid setting off an unnecessary alarm. This assumption is in line with the finding by Flannagan et al. (2016) that alarm rates decreased over time in the scenarios where the ego and the lead vehicle did not remain in the same lane after the FCA was issued.

9.3 The Effects of Reducing Unnecessary Alarms

In Study 4, the findings of Study 1 and 2 were used to test an FCA system adapted to drivers' actual need for assistance dependent on their current manoeuvre intention. Drivers either used a conventional FCA system that activated as many unnecessary as useful alarms, or one of two different adaptive FCA systems that activated only useful alarms and suppressed unnecessary alarms. One adaptive system simply suppressed unnecessary alarms, while the other adaptive system displayed the explanation for alarm suppression in the HUD.

The results showed that drivers were able to understand the activation strategy of the adaptive system without the need for an explicit explanation. Thus, the adaptive system did not impair the development of an appropriate mental model. It was assumed that system understanding would represent the prerequisite for the adaptive system to have a positive effect on drivers' system trust and acceptance. Drivers perceived higher trust in the adaptive systems than in the conventional system. While their trust in the adaptive systems increased during system usage, the trust in the conventional system remained at a constant level. It is assumed that drivers learned that the adaptive system is reliably able to differentiate between situations in which an FCA is either useful or unnecessary and, therefore, their system trust increased over time. In contrast to the positive effect on system trust, the results did not reveal a difference between drivers' acceptance of the conventional FCA system and the adaptive systems. It seems that drivers appreciate the benefits of correct alarms activated by an FCA system so much that – at least in the short term – unnecessary alarms do not significantly decrease system acceptance. In Study 3, the acceptance ratings of unnecessary alarms also varied in the middle range rather than in the lower range of the corresponding scale. This assumption is additionally supported by the deactivation rate of the FCA system with auditory alarms in the naturalistic driving study by Flannagan et al. (2016). The authors defined the deactivation rate as the primary measure of system acceptance in the field (see Section 2.3.5). Despite the high rate of unnecessary FCAs, the system off time was only 17 %. In comparison, the LDW system off time was much higher with 71 % (with auditory alarms).

9.4 Limitations and Future Research

When interpreting the findings of this thesis, some limitations must be considered. This section discusses general limitations of the conducted studies, while study specific limitations are addressed in the related chapters. Associated therewith, this section gives suggestions for future research.

Data of driving simulator studies do not necessarily transfer directly to driving behaviour and subjective evaluations under real traffic conditions (Purucker, Rüger, Schneider, Neukum, & Färber, 2014; Purucker, Schneider, Rüger, & Frey, 2017; Shinoda et al., 2001). The driving simulator setting enabled a high standardisation and a controlled manipulation of the independent variables. Additionally, participants took part in a training that should ensure the transferability of driving behaviour in the simulator to reality (Hoffmann et al., 2003). However, the tested scenarios were less complex and offered less variability compared to driving in real traffic. Despite this limitation, it is assumed that the results of the conducted driving simulator studies provide relative validity (Blaauw, 1982). This means that relative differences between experimental conditions in the driving simulator have the same order and direction as under real driving conditions, even if the absolute values may differ. For example, it can be assumed that the absolute differences between subjective evaluations of FCA systems that regularly activate unnecessary alarms and more reliable FCA systems are greater when being used during every day driving.

In all studies of this thesis, participants were actively forced into the traffic situations with dissolving outcomes. These situations were always caused by the behaviour of other road users. This method might represent a limitation as drivers' advantage over the system in anticipating a dissolving outcome of a conflict became relevant just a maximum of two seconds before a potential crash could have happened. Under real driving conditions, unnecessary alarms are presumably usually caused by the driving behaviour of ego drivers themselves. In these situations, they intentionally approach a standing or braking lead vehicle at constant speed, either as a prelude to change lanes or to turn (considering their own manoeuvre intention) or because they are able to anticipate the other's intention to turn out of their lane until this place is reached. Thereby, they provoke TTC values that result in a high system risk assessment and, finally, activate an unnecessary alarm. In the driving simulator studies of this thesis, it would have been difficult to manipulate such a driving behaviour. In the simulator training in which every participant of Study 1, 3, and 4 had taken part, drivers were trained to drive safely (Hoffmann et al., 2003). In general, most participants drive cautiously and rule-compliantly when taking part in a driving simulator study. It is assumed that drivers might have had an even higher advantage over the system in anticipating the outcome of the conflict if they themselves had provoked the traffic constellation resulting in unnecessary alarms. They would have had more time to perceive all relevant cues, integrate them into a holistic comprehension of the situation, and anticipate the further situational development. This methodological limitation might have decreased effects of manoeuvre intentions and intentions attributed to other road users on the measured variables. It is assumed that unnecessary alarms could result in more negative subjective evaluations when they are a result of the described driving behaviour.

The research of this thesis did not take into account interpersonal and intrapersonal differences that might influence the rate of received unnecessary alarms under real traffic conditions and related subjective evaluations of unnecessary alarms. Previous research showed that alarm rates under naturalistic driving conditions varied greatly between individuals, from 0.08/100 miles to 4.34/100 miles (General Motors Corporation, 2005). Furthermore, men are more likely than women and younger drivers more likely than older drivers to perceive alarms as unnecessary (Eichelberger & McCartt, 2016; Nodine et al., 2011). It is conceivable that drivers with "aggressive" driving styles who consciously take the risk to provoke a low TTC by closely approaching another road user receive more FCAs than drivers with a more "cautious" driving style. This higher overall rate of FCAs might also include a higher rate of alarms perceived as unnecessary for “aggressive” than for “cautious” drivers. Presumably, “aggressive” drivers will be more annoyed by unnecessary alarms and evaluate them as more negative than “cautious” drivers who generally receive a lower rate of unnecessary alarms. Furthermore, driving styles and, thus, the number of experienced unnecessary alarms, and subjective evaluations of unnecessary alarms could also differ dependent on drivers’ current state, e.g. their stress level. Future research could examine the impact of interpersonal and intrapersonal differences on unnecessary alarm rates and subjective evaluations of unnecessary alarms.

An additional subject of future investigation should be the identification and examination of further variables that influence drivers’ retrospective subjective hazard perception and, hence, their perceived need for assistance. For example, in Studies 1 and 2, evaluations of subjective hazard perception and perceived need for assistance differed between traffic scenarios. Events with vulnerable road users in combination with low TTC values led to higher ratings of subjective hazard perception and perceived need for assistance compared to other events involving another car as conflict partner (Figure 5-4). These events were probably perceived as more hazardous because a collision with a vulnerable road user would have had more severe consequences than with another car. To improve the adaption of driver assistance to drivers’ needs, it would be useful to examine the influence of environmental factors like vulnerability of the involved road user on subjective hazard perception and perceived need for assistance. This could expand research by Kassner (2011) concerning driver assistance that should be adapted to task demands influenced by variable situational conditions.

This thesis purposely examined drivers’ *self-reported* perceived need for assistance while neglecting implicit measures for need for assistance. Future research should aim to replicate the results by measuring need for assistance implicitly, for example, by comparing the number of critical situations in different non-assisted driving situations.

Future research should investigate the development of drivers’ responses to unnecessary alarms in real traffic. The development of schemata that enable drivers to anticipate and cross-check the validity of unnecessary alarms might be more difficult and would require more time under real traffic conditions than in the simulation environment. If drivers were able to develop appropriate schemata and learn action-effect relations within a quite short period of time even in real traffic, unnecessary alarms would not be very critical from a safety perspective. Drivers would react with unnecessary braking responses only a limited number of times before the learning process would enable them to reduce the intensity of responses to unnecessary alarms. In addition, to develop a more complete picture of drivers' acceptance of FCA systems that regularly activate unnecessary alarms, further research needs to examine long-term effects of such systems in the field. It would be important to identify which particular experiences with the system or which relation between correct and unnecessary alarms ultimately cause drivers to develop a low system acceptance and to deactivate the system.

Furthermore, this thesis did not investigate the development of driver responses to unnecessary alarms in situations with *unpredictable* dissolving outcome with increasing experiences. It is assumed that drivers cannot develop appropriate schemata for such situations and, thus, unnecessary alarms might intensify driver responses compared to driving behaviour without alarms also in the long term. Moreover, prior research has provided contradictory findings on the effect of unnecessary alarms on compliance with correct alarms (Cotté et al., 2001; Lees & Lee, 2007; Naujoks et al., 2016; Sullivan et al., 2008). To evaluate the overall impact of unnecessary alarms on driving performance, it is important to examine if frequently issued unnecessary alarms impair drivers' reactions to correct alarms in the longer term, e.g. decrease reaction rates and increase reaction times (cry wolf effect, see Section 2.3.4).

Additionally, further research needs to examine the transferability of the present findings concerning FCA systems to other ADAS, such as LDW systems, and systems that intervene instead of warn the driver, and to other alarm systems in general.

9.5 Practical Implications

Alarm activation strategies that base their risk assessment on physical measurements were initially designed for the worst-case scenario in which the driver is inattentive. Although the implemented algorithms are useful and improve driver performance in imminent collision situations (e.g. Lee et al., 2002; Lees & Lee, 2007), the results of this thesis provide evidence that alarm activation strategies of conventional FCA systems might be too simple to meet the perceived need for assistance of attentive drivers. The findings clearly support the relevance of drivers' retrospective subjective hazard perception for their perceived need for assistance. Drivers perceive collision alarms as unnecessary if there is a mismatch between system risk assessment and their subjective hazard perception. An activation strategy associated with situations which average drivers usually perceive as hazardous in retrospect seems to be a promising approach to reduce the rate of unnecessary alarms. To decrease discrepancies between system risk assessment and drivers' subjective hazard perception, the results highlight the importance of considering human factors for warning algorithms of FCA systems. Instead of basing its prediction, risk assessment, and alarm decision exclusively on physical measurements, the system needs to consider factors that human drivers take into account for their anticipation of the outcome of the situation and, thus, for their subjective hazard perception and perceived need for assistance. The results of this thesis identified drivers' current manoeuvre intention and intentions attributed to other road users as relevant factors. An integration of these information on the prediction level would enable the FCA system to decide if a potential conflict will remain or dissolve.

The adaption parameter most frequently used and investigated in prior research is visual attention. However, the results of this thesis imply that visual attention alone represents an inappropriate adaption parameter (see Section 2.4.2.2). Participants in the conducted studies of this thesis were always visually attentive. Nevertheless, their retrospective subjective hazard perceptions and perceived need for assistance varied dependent on their current anticipations. Additionally, a driver who is looking at the road does not necessarily have a correct situation awareness (Schmidt, 2012). Therefore, it is not always suitable to suppress alarms when drivers have their eyes on the road. The system would need much more information about the driver before it should suppress alarms in situations with low TTC values and a dissolving outcome of the conflict. It would additionally need information about the current cognitive workload level to decide if the driver is able to comprehend the situation and to correctly anticipate its further development. Therefore, it is important to emphasise that the findings of this thesis should not yet be used to suppress alarms under the condition that an attentive driver would anticipate a dissolving outcome of a conflict. It must be considered that unnecessary alarms caused moderate braking reactions only in the beginning. The response intensity decreased with increasing system experience. Furthermore, while drivers accepted unnecessary alarms less than useful alarms, their overall system acceptance was not reduced by unnecessary alarms, at least not in the short term. Based on these results, the impact of unnecessary alarms on drivers' behaviour and subjective evaluations does not appear to be harmful enough to take the risk of missing alarms in hazardous situations. If the effects of unnecessary alarms on driver responses and acceptance had been more detrimental, the actual need to shift thresholds and to completely suppress unnecessary alarms would have been higher. Nevertheless, it is important to examine the long-term effects of unnecessary alarms on acceptance and driving behaviour as they are assumed to be more severe.

There remain technological challenges in order to extend the system's situation awareness and, more specifically, its prediction. Building on prior work to predict the next planned driving manoeuvre (e.g. Cheng & Trivedi, 2006; Doshi & Trivedi, 2009; McCall & Trivedi, 2009; Rodemerk et al., 2015; Smith & Zhang, 2004), the challenge now is to further develop algorithms that reliably predict drivers' manoeuvre intentions. For the prediction of subsequent actions of other road users, the system could make use of artificial intelligence. Thereby, the system will be able to learn from experience comparable to human drivers (Bengler et al., 2014; Goodfellow, Bengio, & Courville, 2017). The observation of a large number of objects in the environment enables the system to identify stereotypical traffic situations and, thereby, to make accurate predictions about the behaviour of the driver and other road users. Although artificial intelligence is currently mainly used in the field of automated driving (e.g. Augustin, Hofmann, & Konigorski, 2018), FCA systems might also profit from its application to improve the system's prediction in complex driving situations. Moreover, V2X is a promising technology to consider actions of other road users for anticipation.

Additionally, the knowledge gained in this thesis has implications for automated driving. The situation awareness of an automated driving system needs to approach that of a human driver to offer a natural driving experience. Therefore, the system needs to take into account the same factors as the human driver. Instead of carrying out a hard braking manoeuvre in potentially critical situations (TTC < threshold) with dissolving outcomes, the system should consider its own manoeuvre intention based on the programmed navigation destination and the subsequent actions of other road users.

To sum up, the insights gained by this thesis provide an important element to tailor alarm activation of FCA systems to drivers' actual need for assistance. However, further research and technological improvements are important prerequisites for the implementation of safe adaption strategies. Additionally, the findings provide indications of factors that must be considered by automated driving systems to ensure a natural driving experience.

10 Conclusion

The research in this thesis investigated which psychological factors and processes influence drivers' perceived need for assistance in potential collision situations. The findings showed that the developed theoretical framework of drivers' subjective alarm evaluation (Figure 3-1) is useful to understand the underlying processes that cause drivers to perceive certain collision alarms as unnecessary. The results provided evidence that drivers have advantages over a conventional FCA system in anticipating the further course of a potentially critical situation. While the system's prediction is usually based on TTC values, this thesis showed that drivers' anticipation additionally considers their own current manoeuvre intentions and those attributed to other road users. Thereby, traffic constellations with identical TTC values can result in different human anticipations. As soon as the current TTC value falls below a predefined threshold, the system predicts a potential crash which leads to a high risk assessment and an alarm activation. If drivers anticipate a dissolving outcome of the potential conflict, they do not perceive the situation as hazardous in retrospect. As a consequence, the system's risk assessment is higher than drivers' retrospective subjective hazard perception. The results revealed that drivers' retrospective subjective hazard perception determines their perceived need for assistance. Under the described conditions, drivers' perceived need for assistance is low and, therefore, they perceive the activated alarm as unnecessary.

Unnecessary alarms seem to be more acceptable and pardonable when neither drivers themselves nor the system can anticipate that the conflict will finally dissolve. Drivers indicated a lower acceptance for unnecessary alarms when they had an advantage over the system in anticipating the outcome of the conflict. Nevertheless, drivers' overall acceptance of an FCA system with a 50 % unnecessary alarm rate and an adaptive FCA system without any unnecessary alarm did not differ. At least in the short term, drivers seem to appreciate the benefits of correct FCAs so much that unnecessary alarms do not have a detrimental impact on their system acceptance. It is assumed that system acceptance decreases with long-term experiences with unnecessary alarms in real traffic. Future research should address this open research question.

With regard to drivers' responses to unnecessary alarms, the findings of this thesis provided evidence that drivers go through a learning process. While they showed moderate braking responses without prior experiences with unnecessary alarms, the intensity of responses decreased with multiple exposures. It is assumed that drivers were able to develop schemata consisting of traffic constellations that usually activate unnecessary alarms and that they learned and adapted action-related effects in this specific context. This knowledge enabled them to anticipate unnecessary alarms and to select a less intensive alarm response. If drivers were able to learn to reduce the intensity of their alarm responses even under real traffic conditions, it could be concluded that unnecessary alarms only have a minor negative impact on traffic safety. To obtain a complete picture, there is a need for future research that investigates the effects of unnecessary alarms on driving behaviour in the longer term and under real traffic conditions.

The results contribute to the development of assistance systems adapted to users' needs. The findings are useful to build a bridge between human and machine situation awareness. However, before the knowledge gained in this thesis should be implemented into existing warning algorithms, further research must investigate the role of additional factors that might influence the need for assistance, e.g. cognitive workload, and develop methods that validly measure drivers' intentions and situation awareness. Although unnecessary alarm rates of approximately 50 % are insufficient for present-day FCA systems (Flannagan et al., 2016; General Motors Corporation, 2005), the negative impact of unnecessary alarms on drivers' alarm responses and acceptance seems to remain within tolerable limits. Therefore, unnecessary alarms should not be suppressed prematurely as this, in turn, carries a risk of missing potential collision situations.

This thesis provides a meaningful theoretical evidence for psychological factors and processes that render collision alarms unnecessary in the eyes of human drivers. The results revealed that drivers' current manoeuvre intentions and those attributed to other road users lead to different anticipations of the outcome of physically identical traffic situations. As FCA systems base their prediction exclusively on physical measurements, discrepancies between human and machine situation awareness of the same situation can evolve and result in different subjective evaluations and driving behaviour.

11 References

Abe, G., Itoh, M., & Tanaka, K. (2002). Dynamics of Drivers' Trust in Warning Systems. *IFAC Proceedings Volumes*, *35*(1), 363–368. https://doi.org/10.3182/20020721-6-ES-1901.01614

Abe, G., & Richardson, J. (2006). Alarm Timing, Trust and Driver Expectation for Forward Collision Warning Systems. *Applied Ergonomics*, *37*(5), 577–586. https://doi.org/10.1016/j.apergo.2005.11.001

Ahlstrom, U., & Friedman-Berg, F. J. (2006). Using Eye Movement Activity as a Correlate of Cognitive Workload. *International Journal of Industrial Ergonomics*, *36*(7), 623–636. https://doi.org/10.1016/j.ergon.2006.04.002

Ansuini, C., Cavallo, A., Bertone, C., & Becchio, C. (2015). Intentions in the Brain: The Unveiling of Mister Hyde. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *21*(2), 126–135. https://doi.org/10.1177/1073858414533827

Ansuini, C., Giosa, L., Turella, L., Altoè, G., & Castiello, U. (2008). An Object for an Action, the Same Object for Other Actions: Effects on Hand Shaping. *Experimental Brain Research*, *185*(1), 111–119. https://doi.org/10.1007/s00221-007-1136-4

Augustin, D., Hofmann, M., & Konigorski, U. (2018). Motion Pattern Recognition for Maneuver Detection and Trajectory Prediction on Highways. In *2018 IEEE International Conference on Vehicular Electronics and Safety (ICVES)* (pp. 1–8). Madrid, Spain. https://doi.org/10.1109/ICVES.2018.8519494

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (pp. 47–89). New York: Academic Press. https://doi.org/10.1016/S0079-7421(08)60452-1

Baron, R. M., & Kenny, D. A. (1986). The Moderator–Mediator Variable Distinction in Social Psychological Research: Conceptual, Strategic, and Statistical Considerations. *Journal of Personality and Social Psychology*, *51*(6), 1173–1182. https://doi.org/10.1037/0022-3514.51.6.1173

Bartlett, F. C. (1932). *Remembering: A Study in Experimental and Social Psychology*. Cambridge: Cambridge University Press.

Bauer, D. J., Preacher, K. J., & Gil, K. M. (2006). Conceptualizing and Testing Random Indirect Effects and Moderated Mediation in Multilevel Models: New Procedures and Recommendations. *Psychological Methods*, *11*(2), 142–163. https://doi.org/10.1037/1082-989X.11.2.142

Baumann, M., & Krems, J. F. (2007). Situation Awareness and Driving: A Cognitive Model. In P. C. Cacciabue (Ed.), *Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems* (pp. 253–265). London: Springer.

Baumann, M., Petzoldt, T., Groenewoud, C., Hogema, J., & Krems, J. F. (2008). The Effect of Cognitive Tasks on Predicting Events in Traffic. In C. Brusque (Ed.), *Proceedings of European Conference on Human Centred Design for Intelligent Transportation Systems* (pp. 3–12). Lyon, France: HUMANIST Publications.

Beggiato, M. (2015). Changes in Motivational and Higher Level Cognitive Processes when Interacting with In-Vehicle Automation (Doctoral Dissertation). Technical University Chemnitz. Retrieved from http://nbn-resolving.de/urn:nbn:de:bsz:ch1-qucosa-167333

Bengler, K., Dietmayer, K., Farber, B., Maurer, M., Stiller, C., & Winner, H. (2014). Three Decades of Driver Assistance Systems: Review and Future Perspectives. *IEEE Intelligent Transportation Systems Magazine*, *6*(4), 6–22. https://doi.org/10.1109/MITS.2014.2336271

Blaauw, G. J. (1982). Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study. *Human Factors*, *24*(4), 473–486. https://doi.org/10.1177/001872088202400408

Blaschke, C., Breyer, F., Färber, B., Freyer, J., & Limbacher, R. (2009). Driver Distraction Based Lane-Keeping Assistance. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(4), 288–299. https://doi.org/10.1016/j.trf.2009.02.002

Bliss, J. P., & Acton, S. A. (2003). Alarm Mistrust in Automobiles: How Collision Alarm Reliability Affects Driving. *Applied Ergonomics*, *34*(6), 499–509. https://doi.org/10.1016/j.apergo.2003.07.003

Bliss, J. P., & Gilson, R. D. (1998). Emergency Signal Failure: Implications and Recommendations. *Ergonomics*, *41*(1), 57–72. https://doi.org/10.1080/001401398187323

Bonini, L., Ferrari, P. F., & Fogassi, L. (2013). Neurophysiological Bases Underlying the Organization of Intentional Actions and the Understanding of Others' Intention. *Consciousness and Cognition*, *22*(3), 1095–1104. https://doi.org/10.1016/j.concog.2013.03.001

Bonini, L., Rozzi, S., Serventi, F. U., Simone, L., Ferrari, P. F., & Fogassi, L. (2010). Ventral Premotor and Inferior Parietal Cortices Make Distinct Contribution to Action Organization and Intention Understanding. *Cerebral Cortex*, *20*(6), 1372–1385. https://doi.org/10.1093/cercor/bhp200

Braitman, K. A., McCartt, A. T., Zuby, D. S., & Singer, J. (2010). Volvo and Infiniti Drivers' Experiences with Select Crash Avoidance Technologies. *Traffic Injury Prevention*, *11*(3), 270–278. https://doi.org/10.1080/15389581003735600

Braun, C. C., & Shaver, E. F. (1999). Warning Sign Components and Hazard Perceptions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *43*(16), 878–882. https://doi.org/10.1177/154193129904301601

Breznitz, S. (1984). *Cry Wolf: The Psychology of False Alarms*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Brouwer, R., & Hoedemaeker, D. M. (2005). *Driver Support and Information Systems: Experiments on Learning, Appropriation and Effects of Adaptiveness: Final Deliverable (Del. 1.2.3) of the AIDE IP Research Project*. Brussels: Commission of the European Union-DG Information Society and Media.

Brown, T., Marshall, D., Moeckli, J., & Smyser, T. (2007). *A Final Report of SAfety VEhicle(s) using adaptive Interface Technology (SAVE-IT) Program: Task 14a Evaluation.*

Bustamante, E. A. (2008). Implementing Likelihood Alarm Technology in Integrated Aviation Displays for Enhancing Decision-Making: A Two-Stage Signal Detection Modeling Approach. *The International Journal of Applied Aviation Studies*, *8*(2), 241–260.

Cacciabue, P. C. (Ed.). (2007). *Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems*. London: Springer.

Chancey, E. T. (2016). The Effects of Alarm System Errors on Dependence: Moderated Mediation of Trust With and Without Risk (Doctoral Dissertation). Old Dominion University. Retrieved from https://digitalcommons.odu.edu/cgi/viewcontent.cgi?referer=https://www.google.de/&httpsredir=1&article=1020&context=psychology_etds

Chancey, E. T., Bliss, J. P., Liechty, M., & Proaps, A. B. (2016). False Alarms vs. Misses. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *59*(1), 647–651. https://doi.org/10.1177/1541931215591141

Charlton, S. G., Starkey, N. J., Perrone, J. A., & Isler, R. B. (2014). What's the Risk? A Comparison of Actual and Perceived Driving Risk. *Transportation Research Part F: Traffic Psychology and Behaviour*, *25*, 50–64. https://doi.org/10.1016/j.trf.2014.05.003

Cheng, S. Y., & Trivedi, M. M. (2006). Turn-Intent Analysis Using Body Pose for Intelligent Driver Assistance. *IEEE Pervasive Computing*, *5*(4), 28–37. https://doi.org/10.1109/MPRV.2006.88

Cherri, C., Nodari, E., & Toffetti, A. (2004). *Review of Existing Tools and Methods: Evaluation and Assessment Methodology*. Deliverable 2.1.1 (AIDE: Adaptive Integrated Driver-Vehicle Interface).

Cohen, J. D., & Huston, T. A. (1994). Progress in the Use of Interactive Models for Understanding Attention and Performance. In C. A. Umiltà & M. Moscovitch (Eds.), *Conscious and Nonconscious Information Processing* (pp. 453–456). Cambridge, Mass: MIT Press.

Connor, C. E., Egeth, H. E., & Yantis, S. (2004). Visual Attention: Bottom-Up Versus Top-Down. *Current Biology*, *14*(19), 850–852. https://doi.org/10.1016/j.cub.2004.09.041

Cotté, N., Meyer, J., & Coughlin, J. F. (2001). Older and Younger Drivers' Reliance on Collision Warning Systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *45*(4), 277–280. https://doi.org/10.1177/154193120104500402

Crundall, D. (2016). Hazard Prediction Discriminates Between Novice and Experienced Drivers. *Accident Analysis & Prevention*, *86*, 47–58. https://doi.org/10.1016/j.aap.2015.10.006

Cummings, M. L., Kilgore, R. M., Wang, E., Tijerina, L., & Kochhar, D. S. (2007). Effects of Single Versus Multiple Warnings on Driver Performance. *Human Factors*, *49*(6), 1097–1106. https://doi.org/10.1518/001872007X249956

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly*, *13*(3), 319–340.

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User Acceptance of Computer Technology: A Comparison of Two Theoretical Models. *Management Science*, *35*(8), 982–1003. https://doi.org/10.1287/mnsc.35.8.982

De Waard, D. (1996). The Measurement of Drivers' Mental Workload (Doctoral Dissertation). Groningen University. Retrieved from http://apps.usd.edu/coglab/schieber/pdf/deWaard-Thesis.pdf

Dingus, T. A., Guo, F., Lee, S., Antin, J. F., Perez, M., Buchanan-King, M., & Hankey, J. (2016). Driver Crash Risk Factors and Prevalence Evaluation Using Naturalistic Driving Data. *Proceedings of the National Academy of Sciences*, *113*(10), 2636–2641. https://doi.org/10.1073/pnas.1513271113

Dingus, T. A., McGehee, D. V., Manakkal, N., Jahns, S. K., Carney, C., & Hankey, J. M. (1997). Human Factors Field Evaluation of Automotive Headway Maintenance/Collision Warning Devices. *Human Factors*, *39*(2), 216–229. https://doi.org/10.1518/001872097778543930

Dixon, S. R., Wickens, C. D., & McCarley, J. S. (2007). On the Independence of Compliance and Reliance: Are Automation False Alarms Worse Than Misses? *Human Factors*, *49*(4), 564–572. https://doi.org/10.1518/001872007X215656

Doshi, A., & Trivedi, M. M. (2009). On the Roles of Eye Gaze and Head Dynamics in Predicting Driver's Intent to Change Lanes. *IEEE Transactions on Intelligent Transportation Systems*, *10*(3), 453–462. https://doi.org/10.1109/TITS.2009.2026675

Doshi, A., & Trivedi, M. (2008). A Comparative Exploration of Eye Gaze and Head Motion Cues for Lane Change Intent Prediction. In *2008 IEEE Intelligent Vehicles Symposium (IV)* (pp. 49–54). Eindhoven, the Netherlands. https://doi.org/10.1109/IVS.2008.4621321

Doshi, A., & Trivedi, M. M. (2011). Tactical Driver Behavior Prediction and Intent Inference: A Review. In *14th International IEEE Conference on Intelligent Transportation Systems* (pp. 1892–1897). Washington, DC, USA. https://doi.org/10.1109/ITSC.2011.6083128

Edworthy, J., Loxley, S., & Dennis, I. (1991). Improving Auditory Warning Design: Relationship Between Warning Sound Parameters and Perceived Urgency. *Human Factors*, *33*(2), 205–231. https://doi.org/10.1177/001872089103300206

Edworthy, J., & Stanton, N. (1995). A User-Centred Approach to the Design and Evaluation of Auditory Warning Signals: 1. Methodology. *Ergonomics*, *38*(11), 2262–2280. https://doi.org/10.1080/00140139508925267

Eichelberger, A. H., & McCartt, A. T. (2014). Volvo Drivers' Experiences with Advanced Crash Avoidance and Related Technologies. *Traffic Injury Prevention*, *15*(2), 187–195. https://doi.org/10.1080/15389588.2013.798409

Eichelberger, A. H., & McCartt, A. T. (2016). Toyota Drivers' Experiences with Dynamic Radar Cruise Control, Pre-Collision System, and Lane-Keeping Assist. *Journal of Safety Research*, *56*, 67–73. https://doi.org/10.1016/j.jsr.2015.12.002

Eid, M., Gollwitzer, M., & Schmitt, M. (2017). *Statistik und Forschungsmethoden [Statistics and Research Methods]* (4th ed.). Weinheim, Germany: Beltz.

Endsley, M. R. (1988). Design and Evaluation for Situation Awareness Enhancement. *Proceedings of the Human Factors Society Annual Meeting*, *32*(2), 97–101. https://doi.org/10.1177/154193128803200221

Endsley, M. R. (1995). Measurement of Situation Awareness in Dynamic Systems. *Human Factors*, *37*(1), 65–84. https://doi.org/10.1518/001872095779049499

Endsley, M. R. (2000). Theoretical Underpinnings of Situation Awareness: A Critical Review. In M. R. Endsley & D. J. Garland (Eds.), *Situation Awareness: Analysis and Measurement* (pp. 3–32). Mahwah, N.J.: Lawrence Erlbaum Associates.

Farber, E., & Paley, M. (1993). Using Freeway Traffic Data to Estimate the Effectiveness of Rear End Collision Countermeasures. In *Proceedings of the IVHS America Annual Meeting* (pp. 260–268). Washingon, DC, USA.

Feigh, K. M., Dorneich, M. C., & Hayes, C. C. (2012). Toward a Characterization of Adaptive Systems: A Framework for Researchers and System Designers. *Human Factors*, *54*(6), 1008–1024. https://doi.org/10.1177/0018720812443983

Field, A. P., Miles, J., & Field, Z. (2012). *Discovering Statistics Using R*. London: Sage.

Flannagan, C., LeBlanc, D., Bogard, S., Nobukawa, K., Narayanaswamy, P., Leslie, A., & Lobes, K. (2016). *Large-Scale Field Test of Forward Collision Alert and Lane Departure Warning Systems* (DOT HS 812 247). Washington, DC: National Highway Traffic Safety Administration. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812247b-lanedeparturewarningsystems.pdf

Fogassi, L., Ferrari, P. F., Gesierich, B., Rozzi, S., Chersi, F., & Rizzolatti, G. (2005). Parietal Lobe: From Action Organization to Intention Understanding. *Science*, *308*(622), 662–667. https://doi.org/10.1126/science.1106138

Fracker, M. L. (1988). A Theory of Situation Assessment: Implications for Measuring Situation Awareness. *Proceedings of the Human Factors Society Annual Meeting*, *32*(2), 102–106. https://doi.org/10.1177/154193128803200222

Fuller, R. (2000). The Task-Capability Interface Model of the Driving Process. *Recherche Transports Sécurité*, *66*, 47–57. https://doi.org/10.1016/S0761-8980(00)90006-2

Gallese, V., & Goldman, A. (1998). Mirror Neurons and the Simulation Theory of Mind-Reading. *Trends in Cognitive Sciences*, *2*(12), 493–501. https://doi.org/10.1016/S1364-6613(98)01262-5

Garay-Vega, L., & Fisher, D. L. (2005). Can Novice Drivers Recognize Foreshadowing Risks as Easily as Experienced Drivers? In *Proceedings of the Third Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design* (pp. 471–477). Rockport, USA.

Gauss, B. (2008). Evaluation von Situational Risk Assessment Systemen [Evaluation of Situational Risk Assessments Systems] (Doctoral Dissertation). Technical University Berlin. Retrieved from https://depositonce.tu-berlin.de/bitstream/11303/2115/1/Dokument_35.pdf

General Motors Corporation. (2005). *Automotive Collision Avoidance System Field Operational Test: Final Program Report* (DOT HS 809 886). Washington, DC: National Highway Traffic Safety Administration. Retrieved from https://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2005/ACAS%20FOT%20Final%20Program%20Report%20DOT%20HS%20809%20886.pdf

Gérard, N., & Manzey, D. (2010). Are False Alarms not as Bad as Supposed After All? A Study Investigating Operators' Responses to Imperfect Alarms. In D. de Waard, A. Axelsson, M. Berglund, B. Peters, & C. Weikert (Eds.), *Human Factors: A System View of Human, Technology and Organisation* (pp. 55–69). Maastricht, Netherlands: Shaker Publishing.

German Federal Statistical Office. (2017). Verkehr: Verkehrsunfälle, Fachserie 8 Reihe 7. [Traffic Accidents]. Retrieved from https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/VerkehrsunfaelleMonat/VerkehrsunfaelleM2080700171084.pdf?__blob=publicationFile

Getty, D. J., Swets, J. A., Pickett, R., & Gonthier, D. (1995). System Operator Response to Warnings of Danger: A Laboratory Investigation of the Effects of the Predictive Value of a Warning on Human Response Time. *Journal of Experimental Psychology: Applied*, *1*(1), 19–33. https://doi.org/10.1037/1076-898X.1.1.19

Goodfellow, I., Bengio, Y., & Courville, A. (2017). *Deep Learning*. *Adaptive computation and machine learning series*. Cambridge, MA: MIT Press.

Green, D. M., & Swets, J. A. (1966). *Signal Detection Theory and Psychophysics*. Oxford, England: John Wiley & Sons.

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, *24*(2), 95–112. https://doi.org/10.1007/BF02289823

Groeger, J. A., & Chapman, P. R. (1990). Errors and Bias in Assessments of Danger and Frequency of Traffic Situations. *Ergonomics*, *33*(10-11), 1349–1363. https://doi.org/10.1080/00140139008925337

Gugerty, L. J. (1997). Situation Awareness during Driving: Explicit and Implicit Knowledge in Dynamic Spatial Memory. *Journal of Experimental Psychology: Applied*, *3*(1), 42–66. https://doi.org/10.1037/1076-898X.3.1.42

Gugerty, L. J. (2011). Situation Awareness in Driving. In D. L. Fisher (Ed.), *Handbook of Driving Simulation for Engineering, Medicine, and Psychology* (pp. 265–272). Boca Raton: Taylor & Francis Group.

Hajek, W., Gaponova, I., Fleischer, K. H., & Krems, J. (2013). Workload-Adaptive Cruise Control – A New Generation of Advanced Driver Assistance Systems. *Transportation Research Part F: Traffic Psychology and Behaviour*, *20*, 108–120. https://doi.org/10.1016/j.trf.2013.06.001

Hale, A. R., Stoop, J., & Hommels, J. (1990). Human Error Models as Predictors of Accident Scenarios for Designers in Road Transport Systems. *Ergonomics*, *33*(10-11), 1377–1387. https://doi.org/10.1080/00140139008925339

Hammoud, R. I., Smith, M. R., Dufour, R., Bakowski, D., & Witt, G. (2008). Driver Distraction Monitoring and Adaptive Safety Warning Systems. In *Commercial Vehicle Engineering Congress & Exhibition.* Warrendale, PA, USA: SAE International. https://doi.org/10.4271/2008-01-2694

Hayes, A. F. (2015). An Index and Test of Linear Moderated Mediation. *Multivariate Behavioral Research*, *50*(1), 1–22. https://doi.org/10.1080/00273171.2014.962683

Heller, O. (1985). Hörfeldaudiometrie mit dem Verfahren der Kategorienunterteilung (KU) [Auditory Sensation Audiometry with the Category Sectioning Procedure]. *Psychologische Beiträge*, *27*, 478–493.

Hellier, E., & Edworthy, J. (1999). On Using Psychophysical Techniques to Achieve Urgency Mapping in Auditory Warnings. *Applied Ergonomics*, *30*(2), 167–171. https://doi.org/10.1016/S0003-6870(97)00013-6

Herbart, J. F. (1825). *Psychologie als Wissenschaft neu gegründet auf Erfahrung, Metaphysik und Mathematik [Psychology as a Science Newly Founded on Experience, Metaphysics, and Mathematics]*. Königsberg: August Wilhelm Unzer.

Hershenson, M. (1962). Reaction Time as a Measure of Intersensory Facilitation. *Journal of Experimental Psychology*, *63*(3), 289–293. https://doi.org/10.1037/h0039516

Hjälmdahl, M., & Thorslund, B. (2006). An Adaptive Frontal Collision Warning System on Slippery Roads. In *Proceedings of Transport Research Arena Europe: Greener, Safer and Smarter Road Transport for Europe.* Gothenburg, Sweden.

Ho, C.-Y., & Sarter, N. B. (2016). Supporting Synchronous Distributed Communication and Coordination through Multimodal Information Exchange. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *48*(3), 426–430. https://doi.org/10.1177/154193120404800332

Ho, C., Reed, N., & Spence, C. (2007). Multisensory In-Car Warning Signals for Collision Avoidance. *Human Factors*, *49*(6), 1107–1114. https://doi.org/10.1518/001872007X249965

Hoffmann, J. (2009). ABC: A Psychological Theory of Anticipative Behavioral Control. In D. Hutchison, F. Mattern, J. C. Mitchell, M. Naor, O. Nierstrasz, C. Pandu Rangan,. . . J. M. Kleinberg (Eds.), *Anticipatory Behavior in Adaptive Learning Systems: From Psychological Theories to Artificial Cognitive Systems* (pp. 10–30). Berlin, Heidelberg: Springer.

Hoffmann, S., & Buld, S. (2006). Darstellung und Evaluation eines Trainings zum Fahren in der Fahrsimulation [Driving in a Simulator. Design and Evaluation of a Training Programme]. In VDI-Berichte Nr. 1960 (Ed.), *Integrierte Sicherheit und Fahrerassistenzsysteme* (pp. 113–132). Düsseldorf: VDI-Verlag.

Hoffmann, S., Krüger, H.-P., & Buld, S. (2003). Vermeidung von Simulator Sickness anhand eines Trainings zur Gewöhnung an die Fahrsimulation [Avoidance of Simulator Sickness by Training the Adaptation to the Driving Simulation]. In VDI-Berichte Nr. 1745 (Ed.), *Simulation und Simulatoren — Mobilität Virtuell Gestalten* (pp. 385–404). Düsseldorf: VDI-Verlag.

Horrey, W. J., & Wickens, C. D. (2004). Driving and Side Task Performance: The Effects of Display Clutter, Separation, and Modality. *Human Factors*, *46*(4), 611–624. https://doi.org/10.1518/hfes.46.4.611.56805

Hox, J. J. (2010). *Multilevel Analysis: Techniques and Applications* (2nd ed.). *Quantitative methodology series*. London: Routledge.

Inagaki, T. (2008). Smart Collaboration Between Humans and Machines Based on Mutual Understanding. *Annual Reviews in Control*, *32*(2), 253–261. https://doi.org/10.1016/j.arcontrol.2008.07.003

International Organization for Standardization (2002). *Transport Information and Control Systems — Adaptive Cruise Control Systems — Performance Requirements and Test Procedures*. (ISO Standard No. 15622).

International Organization for Standardization (2016). *Intelligent Transport Systems — External Hazard Detection and Notification Systems — Basic Requirements*. (ISO Standard No. 18682).

Jackson, L., Chapman, P., & Crundall, D. (2009). What Happens Next? Predicting Other Road Users' Behaviour as a Function of Driving Experience and Processing Time. *Ergonomics*, *52*(2), 154–164. https://doi.org/10.1080/00140130802030714

James, W. (1890/1981). *The Principles of Psychology, Vol. 2*. Cambridge, MA: Harvard University Press.

Janssen, W., & Thomas, H. (1997). In-vehicle Collision Avoidance Support Under Adverse Visibility Conditions. In Y. I. Noy (Ed.), *Ergonomics and Safety of Intelligent Driver Interfaces* (pp. 221–229). Mahwah, N.J.: Lawrence Erlbaum Associates.

Janssen, W. H., & Nilsson, L. (1991). An Experimental Evaluation of In-Vehicle Collision Avoidance Systems. In *Proceedings of the 24th ISATA International Symposium on Automotive Technology and Automation* (pp. 209–214). Florence, Italy.

Jian, J.-Y., Bisantz, A. M., & Drury, C. G. (2000). Foundations for an Empirically Determined Scale of Trust in Automated Systems. *International Journal of Cognitive Ergonomics*, *4*(1), 53–71. https://doi.org/10.1207/S15327566IJCE0401_04

Jones, D. G., & Endsley, M. R. (1996). Sources of Situation Awareness Errors in Aviation. *Aviation Space and Environmental Medicine*, *67*(6), 507–512.

Jones, D. G., & Endsley, M. R. (2000). Overcoming Representational Errors in Complex Environments. *Human Factors*, *42*(3), 367–378. https://doi.org/10.1518/001872000779698187

Jung, T., Kaß, C., Zapf, D., & Hecht, H. (2019). Effectiveness and User Acceptance of Infotainment-Lockouts: A Driving Simulator Study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *60*, 643–656. https://doi.org/10.1016/j.trf.2018.12.001

Kaplan, J. T., & Iacoboni, M. (2006). Getting a Grip on Other Minds: Mirror Neurons, Intention Understanding, and Cognitive Empathy. *Social Neuroscience*, *1*(3-4), 175–183. https://doi.org/10.1080/17470910600985605

Kaß, C., Schmidt, G. J., & Kunde, W. (2018a). Towards an Assistance Strategy that Reduces Unnecessary Collision Alarms: An Examination of the Driver’s Perceived Need for Assistance. *Journal of Experimental Psychology: Applied, 25(2),* 291-302. https://doi.org/10.1037/xap0000184

Kaß, C., Schmidt, G. J., & Kunde, W. (2018b). Understanding the Differences between Human and System Hazard Perception in Potential Collision Situations. In F. Eyssel, S. Kopp, U. Schmid, A. Schulte, A. Kluge, M. Jipp,. . . A. Wendemuth (Eds.), *7. Interdisziplinärer Workshop: Kognitive Systeme: Mensch, Teams, Systeme und Automaten* (pp. 27–35). Braunschweig, Germany.

Kaß, C., Schmidt, G. J., & Kunde, W. (2019). Short-Term Effects of Unnecessary Collision Alarms on Driver Behaviour. In D. de Waard, K. A. Brookhuis, D. Coelho, S. Fairclough, D. Manzey, A. Naumann,. . . R. Wiczorek (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference* (pp. 177–189). Berlin, Germany. Retrieved from https://www.hfes-europe.org/largefiles/proceedingshfeseurope2018.pdf

Kass, S. J., Cole, K. S., & Stanny, C. J. (2007). Effects of Distraction and Experience on Situation Awareness and Simulated Driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *10*(4), 321–329. https://doi.org/10.1016/j.trf.2006.12.002

Kassner, A. (2011). Verbesserung der Wirkung und Akzeptanz von Fahrerassistenzsystemen durch Berücksichtigung der Anforderungen an den Fahrer [Improving Effectiveness and Acceptance of Driver Assistance Systems by Matching Assistance Functions and Task Demands] (Doctoral Dissertation). Technical University Braunschweig. Retrieved from https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00038852

Kiesel, A., & Miller, J. (2007). Impact of Contingency Manipulations on Accessory Stimulus Effects. *Perception & Psychophysics*, *69*(7), 1117–1125. https://doi.org/10.3758/BF03193949

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data*. Retrieved from https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDAQFjAA&url=http%3A%2F%2Fwww.nhtsa.gov%2FDOT%2FNHTSA%2FNRD%2FMultimedia%2FPDFs%2FCrash%2520Avoidance%2FDriver%2520Distraction%2F810594.pdf&ei=HkluUviLNsLtswbAjYH4AQ&usg=AFQjCNHx-BHIU3K36mBqZc-jOnWZpCFqeNA&bvm=bv.55123115,d.Yms

Körber, M. (2015). *Vertrauen in Automation [Trust in Automation]*. Retrieved from https://github.com/moritzkoerber/TiA_Trust_in_Automation_Questionnaire

Kramer, A. F., Cassavaugh, N., Horrey, W. J., Becic, E., & Mayhugh, J. L. (2007). Influence of Age and Proximity Warning Devices on Collision Avoidance in Simulated Driving. *Human Factors*, *49*(5), 935–949. https://doi.org/10.1518/001872007X230271

Kreft, I., & Leeuw, J. d. (1998). *Introducing Multilevel Modeling*. London: Sage.

Kruger, J., & Dunning, D. (1999). Unskilled and Unaware of it: How Difficulties in Recognizing One’s Own Incompetence Lead to Inflated Self-Assessments. *Journal of Personality and Social Psychology*, *77*(6), 1121–1134. https://doi.org/10.1037/0022-3514.77.6.1121

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated Action Effects Affect the Selection, Initiation, and Execution of Actions. *The Quarterly Journal of Experimental Psychology*, *57*(1), 87–106. https://doi.org/10.1080/02724980343000143

Lamme, V. A. (2000). Neural Mechanism of Visual Awareness: A Linking Position. *Brain and Mind*, *1*(3), 385–406. https://doi.org/10.1023/A:1011569019782

Laughery, K. R., & Wogalter, M. S. (2006). Designing Effective Warnings. *Reviews of Human Factors and Ergonomics*, *2*(1), 241–271. https://doi.org/10.1177/1557234X0600200109

LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J., . . . Gordon, T. J. (2006a). *Road Departure Crash Warning System Field Operational Test: Methodology and*

Results: Volume 1: Technical Report (UMTRI-2006-9-1). Retrieved from https://deepblue.lib.umich.edu/bitstream/handle/2027.42/49242/99788.pdf?sequence=1&isAllowed=y

LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J., . . . Gordon, T. J. (2006b). *Road Departure Crash Warning System Field Operational Test: Methodology and Results: Volume 2: Appendices* (UMTRI-2006-9-2).

Lee, J. D., Hoffman, J. D., & Hayes, E. (2004). Collision Warning Design to Mitigate Driver Distraction. In E. Dykstra-Erickson & M. Tscheligi (Eds.), *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 65–72). Vienna, Austria. https://doi.org/10.1145/985692.985701

Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision Warning Timing, Driver Distraction, and Driver Response to Imminent Rear-End Collisions in a High-Fidelity Driving Simulator. *Human Factors*, *44*(2), 314–334. https://doi.org/10.1518/0018720024497844

Lee, S., Klauer, S. G., Olsen, E. C. B., Simons-Morton, B. G., Dingus, T. A., Ramsey, D. J., & Ouimet, M. C. (2008). Detection of Road Hazards by Novice Teen and Experienced Adult Drivers. *Transportation Research Record: Journal of the Transportation Research Board*, *2078*, 26–32. https://doi.org/10.3141/2078-04

Lees, M. N., & Lee, J. D. (2007). The Influence of Distraction and Driving Context on Driver Response to Imperfect Collision Warning Systems. *Ergonomics*, *50*(8), 1264–1286. https://doi.org/10.1080/00140130701318749

Lerner, N. D., Dekker, D. K., Steinberg, G. V., & Huey, R. W. (1996). *Inappropriate Alarm Rates and Driver Annoyance* (DOT HS 808 533). Washington, DC: National Highway Traffic Safety Administration. Retrieved from https://rosap.ntl.bts.gov/view/dot/2760/dot_2760_DS1.pdf?

Lethaus, F., & Rataj, J. (2007). Do Eye Movements Reflect Driving Manoeuvres? *IET Intelligent Transport Systems*, *1*(3), 199–204. https://doi.org/10.1049/iet-its:20060058

Liang, Y., Lee, J., & Reyes, M. (2007). Nonintrusive Detection of Driver Cognitive Distraction in Real Time Using Bayesian Networks. *Transportation Research Record: Journal of the Transportation Research Board*, *2018*, 1–8. https://doi.org/10.3141/2018-01

Limesurvey GmbH. (2012). LimeSurvey: An Open Source Survey Tool. Hamburg, Germany. Retrieved from http://www.limesurvey.org

Liu, Y.-C., & Jhuang, J.-W. (2012). Effects of In-Vehicle Warning Information Displays with or without Spatial Compatibility on Driving Behaviors and Response Performance. *Applied Ergonomics*, *43*(4), 679–686. https://doi.org/10.1016/j.apergo.2011.10.005

Madhavan, P., Wiegmann, D. A., & Lacson, F. C. (2006). Automation Failures on Tasks Easily Performed by Operators Undermine Trust in Automated Aids. *Human Factors*, *48*(2), 241–256. https://doi.org/10.1518/001872006777724408

Malle, B. F., Moses, L. J., & Baldwin, D. A. (2003). *Intentions and Intentionality: Foundations of Social Cognition*. *A Bradford book*. Cambridge, Mass, London.: MIT Press.

Maltz, M., & Shinar, D. (2004). Imperfect In-Vehicle Collision Avoidance Warning Systems Can Aid Drivers. *Human Factors*, *46*(2), 357–366. https://doi.org/10.1518/hfes.46.2.357.37348

Maltz, M., & Shinar, D. (2007). Imperfect In-Vehicle Collision Avoidance Warning Systems Can Aid Distracted Drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, *10*(4), 345–357. https://doi.org/10.1016/j.trf.2007.01.002

McCall, J. C., & Trivedi, M. M. (2009). Driver Behavior and Situation Aware Brake Assistance for Intelligent Vehicles. *Proceedings of the IEEE*, *95*(2), 374–387. https://doi.org/10.1109/JPROC.2007.888388

McClelland, J. L., & Rumelhart, D. E. (1986). *Parallel Distributed Processing: Exploration in the Microstructure of Cognition*. *Computational models of cognition and perception*. Cambridge, Mass: The MIT Press.

McRuer, D. T., Allen, R. W., Weir, D. H., & Klein, R. H. (1977). New Results in Driver Steering Control Models. *Human Factors*, *19*(4), 381–397. https://doi.org/10.1177/001872087701900406

Meltzoff, A. N. (1995). Understanding the Intentions of Others: Re-Enactment of Intended Acts by 18-Month-Old Children. *Developmental Psychology*, *31*(5), 838–850. https://doi.org/10.1037/0012-1649.31.5.838

Meyer, J. (2001). Effects of Warning Validity and Proximity on Responses to Warnings. *Human Factors*, *43*(4), 563–572. https://doi.org/10.1518/001872001775870395

Meyer, J. (2004). Conceptual Issues in the Study of Dynamic Hazard Warnings. *Human Factors*, *46*(2), 196–204. https://doi.org/10.1518/hfes.46.2.196.37335

Michon, J. A. (1985). A Critical View of Driver Behaviour Models: What Do We Know, What Should We Do? In L. Evans & C. Schwing (Eds.), *Human Behavior and Traffic Safety* (pp. 485–520). New York: Plenum Press.

Miller, J. (1982). Divided Attention: Evidence for Coactivation with Redundant Signals. *Cognitive Psychology*, *14*(2), 247–279. https://doi.org/10.1016/0010-0285(82)90010-X

Miller, J., Franz, V., & Ulrich, R. (1999). Effects of Auditory Stimulus Intensity on Response Force in Simple, Go/No-Go, and Choice RT Tasks. *Perception & Psychophysics*, *61*(1), 107–119. https://doi.org/10.3758/BF03211952

Morando, A., Victor, T., & Dozza, M. (2016). Drivers Anticipate Lead-Vehicle Conflicts During Automated Longitudinal Control: Sensory Cues Capture Driver Attention and Promote Appropriate and Timely Responses. *Accident Analysis & Prevention*, *97*, 206–219. https://doi.org/10.1016/j.aap.2016.08.025

Mosier, K. L., & Skitka, L. J. (1996). Human Decision Makers and Automated Decision Aids: Made for Each Other? In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 201–220). Mahwah, N.J.: Lawrence Erlbaum Associates.

Mosier, K. L., Skitka, L. J., Heers, S., & Burdick, M. (1998). Automation Bias: Decision Making and Performance in High-Tech Cockpits. *The International Journal of Aviation Psychology*, *8*(1), 47–63. https://doi.org/10.1207/s15327108ijap0801_3

Mühl, K., & Baumann, M. (2018). The Role of Cognitive Distraction and Characteristics of Situation Elements on Anticipation while Driving. In T. Victor, M. P. Bruyas, M. Regan, C. Brusque, A. Fort, & C. Jallais (Eds.), *Proceedings of the 6th Driver Distraction and Inattention Conference: Driver Engagement during Assisted Driving.* Gothenburg, Sweden.

Muhrer, E., & Vollrath, M. (2011). The Effect of Visual and Cognitive Distraction on Driver's Anticipation in a Simulated Car Following Scenario. *Transportation Research Part F: Traffic Psychology and Behaviour*, *14*(6), 555–566. https://doi.org/10.1016/j.trf.2011.06.003

Muller, D., Judd, C. M., & Yzerbyt, V. Y. (2005). When Moderation is Mediated and Mediation is Moderated. *Journal of Personality and Social Psychology*, *89*(6), 852–863. https://doi.org/10.1037/0022-3514.89.6.852

Naujoks, F., Grattenthaler, H., Neukum, A., Weidl, G., & Petrich, D. (2015). Effectiveness of Advisory Warnings Based on Cooperative Perception. *IET Intelligent Transport Systems*, *9*(6), 606–617. https://doi.org/10.1049/iet-its.2014.0190

Naujoks, F., Kiesel, A., & Neukum, A. (2016). Cooperative Warning Systems: The Impact of False and Unnecessary Alarms on Drivers' Compliance. *Accident Analysis & Prevention*, *97*, 162–175. https://doi.org/10.1016/j.aap.2016.09.009

Navarro, J., Deniel, J., Yousfi, E., Jallais, C., Bueno, M., & Fort, A. (2018). Does False and Missed Lane Departure Warnings Impact Driving Performances Differently? *International Journal of Human–Computer Interaction*, 1–11. https://doi.org/10.1080/10447318.2018.1519166

Navarro, J., Yousfi, E., Deniel, J., Jallais, C., Bueno, M., & Fort, A. (2016). The Impact of False Warnings on Partial and Full Lane Departure Warnings Effectiveness and Acceptance in Car Driving. *Ergonomics*, *59*(12), 1553–1564. https://doi.org/10.1080/00140139.2016.1158323

Neukum, A., Krüger, H. P., Mayser, C., & Steinle, J. (2008). ACC-Stop&Go: Fahrerverhalten an funktionalen Systemgrenzen [ACC Stop&Go: Driver Behavior at Functional System Boundaries]. In M. Maurer & C. Stiller (Eds.), *5. Workshop Fahrerassistenzsysteme — FAS 2008* (pp. 141–150). Karlsruhe, Germany: fmrt.

Nodine, E., Lam, A., Stevens, S., Razo, M., & Najm, W. (2011). *Integrated Vehicle-Based Safety Systems (IVBSS): Light Vehicle Field Operational Test Independent Evaluation* (DOT HS 811 516). Washingon, DC: National Highway Traffic Safety Administration. Retrieved from https://rosap.ntl.bts.gov/view/dot/9512/dot_9512_DS1.pdf?

O'Brien, F., & Cousineau, D. (2014). Representing Error Bars in Within-Subject Designs in Typical Software Packages. *The Quantitative Methods for Psychology*, *10*(1), 56–67. https://doi.org/10.20982/tqmp.10.1.p056

Ohly, S., Sonnentag, S., Niessen, C., & Zapf, D. (2010). Diary Studies in Organizational Research. *Journal of Personnel Psychology*, *9*(2), 79–93. https://doi.org/10.1027/1866-5888/a000009

Parasuraman, R., Hancock, P. A., & Olofinboba, O. (1997). Alarm Effectiveness in Driver-Centred Collision-Warning Systems. *Ergonomics*, *40*(3), 390–399. https://doi.org/10.1080/001401397188224

Parasuraman, R., & Riley, V. (1997). Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors*, *39*(2), 230–253. https://doi.org/10.1518/001872097778543886

Parasuraman, R., Molloy, R., & Singh, I. L. (1993). Performance Consequences of Automation-Induced 'Complacency'. *The International Journal of Aviation Psychology*, *3*(1), 1–23. https://doi.org/10.1207/s15327108ijap0301_1

Pech, T., Enhuber, S., Wandtner, B., Schmidt, G. J., & Wanielik, G. (2019). Real Time Recognition of Non-driving Related Tasks in the Context of Highly Automated Driving. In J. Dubbert, B. Müller, & G. Meyer (Eds.), *Lecture Notes in Mobility. Advanced Microsystems for Automotive Applications 2018: Smart Systems for Clean, Safe and Shared Road Vehicles* (pp. 43–55). Cham: Springer.

Perez, M. A., Kiefer, R. J., Haskins, A., & Hankey, J. M. (2009). Evaluation of Forward Collision Warning System Visual Alert Candidates and SAE J2400. *SAE International Journal of Passenger Cars — Mechanical Systems*, *2*(1), 750–764. https://doi.org/10.4271/2009-01-0547

Petersson, L., Fletcher, L., Barnes, N., & Zelinsky, A. (2004). An Interactive Driver Assistance System Monitoring the Scene In and Out of the Vehicle. In *IEEE International Conference on Robotics and Automation* (pp. 3475–3481). New Orleans, LA, USA. https://doi.org/10.1109/ROBOT.2004.1308791

Pohl, J., Birk, W., & Westervall, L. (2007). A Driver-Distraction-Based Lane-Keeping Assistance System. *Journal of Systems and Control Engineering*, *221*(4), 541–552. https://doi.org/10.1243/09596518JSCE218

Portouli, V., Papanikolopoulos, N., Lai, F., Chorlton, K., Hjälmdahl, M., Wiklund, M., . . . Roland, J. (2006). *Behavioural Effects and Driver-Vehicle-Environment Modelling: Long-Term Phase Test and Results*. *AIDE- Adaptive Integrated Driver-Vehicle Interface*.

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual Dominance: An Information-Processing Account of its Origins and Significance. *Psychological Review*, *83*(2), 157–171. https://doi.org/10.1037/0033-295X.83.2.157

Premack, D., & Woodruff, G. (1978). Does the Chimpanzee Have a Theory of Mind? *Behavioral and Brain Sciences*, *1*(04), 515. https://doi.org/10.1017/S0140525X00076512

Purucker, C., Rüger, F., Schneider, N., Neukum, A., & Färber, B. (2014). Comparing the Perception of Critical Longitudinal Distances between Dynamic Driving Simulation, Test Track and Vehicle in the Loop. In T. Ahram, W. Karwowski, & T. Marek (Eds.), *Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics* (pp. 2089–2098). Kraków, Poland.

Purucker, C., Schneider, N., Rüger, F., & Frey, A. (2017). Validity of Research Environments. In K. Bengler, J. Drüke, S. Hoffmann, D. Manstetten, & A. Neukum (Eds.), *UR:BAN Human Factors in Traffic: Approaches for Safe, Efficient and Stress-free Urban Traffic* (pp. 423–446). Wiesbaden: Springer Fachmedien Wiesbaden.

Qualtrics. (2017). Qualtrics. Provo, Utha, USA: Qualtrics. Retrieved from http://www.qualtrics.com

Raab, D. H. (1962). Division of Psychology: Statistical Facilitation of Simple Reaction Times. *Transactions of the New York Academy of Sciences*, *24*(5), 574–590. https://doi.org/10.1111/j.2164-0947.1962.tb01433.x

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics*, *13*(3), 257–266.

Rauch, N. (2009). Ein verhaltensbasiertes Messmodell zur Erfassung von Situationsbewusstsein im Fahrkontext [A Behavior-Based Measurement Model to assess Situation Awareness in the Driving Context] (Doctoral Dissertation). Julius-Maximilians-University Würzburg. Retrieved from urn:nbn:de:bvb:20-opus-37225

Raudenbush, S. W., Bryk, A. S., & Congdon, R. T. (2013). HLM 7.01 for Windows [Computer Software]. Skokie, IL: Scientific Software International, Inc.

Raudenbush, S. W., Bryk, A. S., Cheong, Y. F., Congdon, R. T., & Du Toit, M. (2011). *HLM 7: Hierarchical Linear and Nonlinear Modeling*. Skokie, IL: Scientific Software International, Inc.

Regan, D., & Vincent, A. (1995). Visual Processing of Looming and Time to Contact Throughout the Visual Field. *Vision Research*, *35*(13), 1845–1857. https://doi.org/10.1016/0042-6989(94)00274-P

Reinmueller, K., Koehler, L., & Steinhauser, M. (2018). Adaptive Warning Signals Adjusted to Driver Passenger Conversation: Impact of System Awareness on Behavioral Adaptations. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 242–252. https://doi.org/10.1016/j.trf.2018.06.013

Rodemerk, C., Winner, H., & Kastner, R. (2015). Predicting the Driver's Turn Intentions at Urban Intersections Using Context-Based Indicators. In *IEEE Intelligent Vehicles Symposium (IV)* (pp. 964–969). Seoul, South Korea. https://doi.org/10.1109/IVS.2015.7225809

Rouse, W. B. (1988). Adaptive Aiding for Human/Computer Control. *Human Factors*, *30*(4), 431–443. https://doi.org/10.1177/001872088803000405

Rouse, W. B., & Morris, N. M. (1986). On Looking into the Black Box: Prospects and Limits in the Search for Mental Models. *Psychological Bulletin*, *100*(3), 349–363. https://doi.org/10.1037/0033-2909.100.3.349

Ruble, D. N., & Stangor, C. (1986). Stalking the Elusive Schema: Insights from Developmental and Social-Psychological Analyses of Gender Schemas. *Social Cognition*, *4*(2), 227–261. https://doi.org/10.1521/soco.1986.4.2.227

SAE International. (2018). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. No. J3016. Retrieved from https://saemobilus.sae.org/content/j3016_201806

Sarter, N. B. (2005). Graded and Multimodal Interruption Cueing in Support of Preattentive Reference and Attention Management. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *49*(3), 478–481. https://doi.org/10.1177/154193120504900356

Schaap, T. W. (2012). Driving Behaviour in Unexpected Situations: A study Into Drivers' Compensation Behaviour to Safety-Critical Situations and the Effects of Mental Workload, Event Urgency and Task Prioritization (Doctoral Dissertation), University of Twente. Retrieved from https://research.utwente.nl/files/6065598/thesis_N_Schaap.pdf

Schmidt, G. (2012). The Influence of Anticipation and Warnings on Collision Avoidance Behavior of Attentive Drivers (Doctoral Dissertation). Julius-Maximilians-University Würzburg. Retrieved from urn:nbn:de:bvb:20-opus-73789

Schwalm, M. (2009). Pupillometrie als Methode zur Erfassung mentaler Beanspruchungen im automotiven Kontext [Pupillometry as a Method to Assess Mental Workload in the Automotive Context] (Doctoral Dissertation). Universität des Saarlandes. Retrieved from https://publikationen.sulb.uni-saarland.de/bitstream/20.500.11880/23353/1/Dissertation_Maximilian_Schwalm.pdf

Schwarz, J., & Fuchs, S. (2014). Adaptive Automation als Sozialer Akteur: Anforderungen an die Gestaltung aus Psychologischer und Systemtheoretischer Sicht [Adaptive Automation as Social Actor: Design Requirements from a Psychological and Systems Theoretical Perspective]. In M. Grandt & S. Schmerwitz (Eds.), *Der Mensch zwischen Automatisierung, Kompetenz und Verantwortung.* Bonn: Deutsche Gesellschaft für Luft- und Raumfahrt – Lilienthal-Oberth e.V.

Selcon, S. J., Taylor, R. M., & McKenna, F. P. (1995). Integrating Multiple Information Sources: Using Redundancy in the Design of Warnings. *Ergonomics*, *38*(11), 2362–2370. https://doi.org/10.1080/00140139508925273

Shinoda, H., Hayhoe, M. M., & Shrivastava, A. (2001). What Controls Attention in Natural Environments? *Vision Research*, *41*(25-26), 3535–3545. https://doi.org/10.1016/S0042-6989(01)00199-7

Simon, J. H. (2005). Learning to Drive with Advanced Driver Assistance Systems: Empirical Studies of an Online Tutor and a Personalised Warning Display on the Effects of Learnability and the Acquisition of Skill (Doctoral Dissertation). Technical University Chemnitz. Retrieved from https://monarch.qucosa.de/api/qucosa%3A18510/attachment/ATT-0/

Simon, K., & Bullinger, A. C. (2018). *To Change or Not to Change – That is the Question: Detecting Lane Change Signals for Anticipatory Highly Automated Driving.* Paper presented at Human Factors and Ergonomic Society – Europe Chapter, Berlin, Germany. Retrieved from https://www.hfes-europe.org/wp-content/uploads/2018/10/Simon2018Poster.pdf

Simons, D. J. (2000). Current Approaches to Change Blindness. *Visual Cognition*, *7*(1-3), 1–15. https://doi.org/10.1080/135062800394658

Sklar, A. E., & Sarter, N. B. (1999). Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains. *Human Factors*, *41*(4), 543–552. https://doi.org/10.1518/001872099779656716

Smith, D. A., & Graesser, A. C. (1981). Memory for Actions in Scripted Activities as a Function of Typicality, Retention Interval, and Retrieval Task. *Memory & Cognition*, *9*(6), 550–559. https://doi.org/10.3758/BF03202349

Smith, M., & Zhang, H. (2004). *SAVE-IT - SAfety VEhicles using adaptive Interface Technology (Task 8): Intent Inference.*

Smith, M., Witt, G., Bakowski, D., LeBlanc, D., & Lee, J. D. (2008). Adapting Collision Warnings to Real-Time Estimates of Driver Distraction. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction: Theory, Effects, and Mitigation* (pp. 501–518). Boca Raton: CRC Press/Taylor & Francis Group.

Smith, S. S., Horswill, M. S., Chambers, B., & Wetton, M. (2009). Hazard Perception in Novice and Experienced Drivers: The Effects of Sleepiness. *Accident Analysis & Prevention*, *41*(4), 729–733. https://doi.org/10.1016/j.aap.2009.03.016

Sorkin, R. D., Kantowitz, B. H., & Kantowitz, S. C. (1988). Likelihood Alarm Displays. *Human Factors*, *30*(4), 445–459. https://doi.org/10.1177/001872088803000406

Sorkin, R. D., & Woods, D. D. (2009). Systems with Human Monitors: A Signal Detection Analysis. *Human–Computer Interaction*, *1*(1), 49–75. https://doi.org/10.1207/s15327051hci0101_2

Stahl, P. (2015). Defining, Investigating and Supporting Anticipatory Driving: A Systematic Investigation of the Competence to Predict Traffic (Doctoral Dissertation). University of Toronto. Retrieved from https://tspace.library.utoronto.ca/bitstream/1807/79728/3/Stahl_Patrick_201511_PhD_thesis.pdf

Stahl, P., Donmez, B., & Jamieson, G. A. (2014). Anticipation in Driving: The Role of Experience in the Efficacy of Pre-event Conflict Cues. *IEEE Transactions on Human-Machine Systems*, *44*(5), 603–613. https://doi.org/10.1109/THMS.2014.2325558

Stahl, P., Donmez, B., & Jamieson, G. A. (2016). Supporting Anticipation in Driving through Attentional and Interpretational In-Vehicle Displays. *Accident Analysis & Prevention*, *91*, 103–113. https://doi.org/10.1016/j.aap.2016.02.030

Stevens, S. (2012). The Relationship between Driver Acceptance and System Effectiveness in Car-Based Collision Warning Systems: Evidence of an Overreliance Effect in Older Drivers? *SAE International Journal of Passenger Cars — Electronic and Electrical Systems*, *5*(1), 114–124. https://doi.org/10.4271/2012-01-0282

Streubel, T., & Hoffmann, K. H. (2014). Prediction of Driver Intended Path at Intersections. In *2014 IEEE Intelligent Vehicles Symposium (IV)* (pp. 134–139). Dearborn, Michigan, USA. https://doi.org/10.1109/IVS.2014.6856508

Stroop, J. R. (1935). Studies of Interference in Serial Verbal Reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Sullivan, J. M., Tsimhoni, O., & Bogard, S. (2008). Warning Reliability and Driver Performance in Naturalistic Driving. *Human Factors*, *50*(5), 845–852. https://doi.org/10.1518/001872008X312332

Swets, J. A. (1992). The Science of Choosing the Right Decision Threshold in High-Stakes Diagnostics. *American Psychologist*, *47*(4), 522–532. https://doi.org/10.1037//0003-066X.47.4.522

Swets, J. A. (2014). *Signal Detection Theory and ROC Analysis in Psychology and Diagnostics: Collected Papers*. *Scientific Psychology Series*. Hoboken: Taylor and Francis. Retrieved from http://gbv.eblib.com/patron/FullRecord.aspx?p=1639290

Taylor, S., & Todd, P. A. (1995). Understanding Information Technology Usage: A Test of Competing Models. *Information Systems Research*, *6*(2), 144–176.

Tijerina, L., Blommer, M., Curry, R., Greenberg, J., Kochhar, D., Simonds, C., & Watson, D. (2010). Effects of Adaptive Lane Departure Warning System on Driver Response to a Surprise Event. *Transportation Research Record: Journal of the Transportation Research Board*, *2185*, 1–7. https://doi.org/10.3141/2185-01

Todd, J. W. (1912). *Reaction to Multiple Stimuli* (Vol. 3): The Science Press.

Trefflich, B. (2010). Videogestützte Überwachung der Fahreraufmerksamkeit und Adaption von Fahrerassistenzsystemen [Video-Based Monitoring of Driver Attention and Adaptation of Driver Assistance Systems] (Doctoral Dissertation). Technical University Ilmenau. Retrieved from https://d-nb.info/100212803x/34

Underwood, G., Ngai, A., & Underwood, J. (2013). Driving Experience and Situation Awareness in Hazard Detection. *Safety Science*, *56*, 29–35. https://doi.org/10.1016/j.ssci.2012.05.025

Van der Laan, J. D., Heino, A., & de Waard, D. (1997). A Simple Procedure For The Assessment Of Acceptance Of Advanced Transport Telematics. *Transportation Research Part C: Emerging Technologies*, *5*(1), 1–10. https://doi.org/10.1016/S0968-090X(96)00025-3

Van Driel, C., & van Arem, B. (2005). Investigation of User Needs for Driver Assistance: Results of an Internet Questionnaire. *European Journal of Transport and Infrastructure Research*, *5*(4), 297–316.

Wallis, T. S. A., & Horswill, M. S. (2007). Using Fuzzy Signal Detection Theory to Determine Why Experienced and Trained Drivers Respond Faster Than Novices in a Hazard Perception Test. *Accident Analysis & Prevention*, *39*(6), 1177–1185. https://doi.org/10.1016/j.aap.2007.03.003

Watts, G. R., & Quimby, A. R. (1980). *Aspects of Road Layout that Affect Drivers' Perception and Risk Taking: TRRL Report 920*. Crowthorne, Berkshire, England: Transport and Road Research Laboratory.

Wegener, D. T., & Fabrigar, L. R. (2000). Analysis and Design for Nonexperimental Data: Addressing Causal and Noncausal Hypotheses. In H. T. Reis & C. M. Judd (Eds.), *Handbook of research methods in social and personality psychology* (pp. 412–450). New York: Cambridge University Press.

Wickens, C., Prinet, J., Hutchins, S., Sarter, N., & Sebok, A. (2011). Auditory-Visual Redundancy in Vehicle Control Interruptions: Two Meta-analyses. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *55*(1), 1155–1159. https://doi.org/10.1177/1071181311551241

Wickens, C. D. (1984). Processing Resources in Attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of Attention* (pp. 63–101). New York: Academic Press.

Wickens, C., & Colcombe, A. (2007). Dual-Task Performance Consequences of Imperfect Alerting Associated with a Cockpit Display of Traffic Information. *Human Factors*, *49*(5), 839–850. https://doi.org/10.1518/001872007X230217

Wickens, C. D., Hollands, J. G., Banbury, S., & Parasuraman, R. (2013). *Engineering Psychology and Human Performance* (4th Ed.). Boston: Pearson.

Wiczorek, R., & Manzey, D. (2010). Is Operators' Compliance with Alarm Systems a Product of Rational Consideration? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *54*(19), 1722–1726. https://doi.org/10.1177/154193121005401976

Wiczorek, R., & Manzey, D. (2011). Evaluating Likelihood Alarm Systems as an Alternative to Binary Alarm Systems. In D. de Waard, K. A. Brookhuis, A. Toffetti, A. Stuiver, C. Weikert, D. Coelho,. . . N. Merat (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2011 Annual Conference* (pp. 69–83). Maastricht, The Netherlands.

Wilson, G. F., & Russell, C. A. (2003). Real-Time Assessment of Mental Workload Using Psychophysiological Measures and Artificial Neural Networks. *Human Factors*, *45*(4), 635–643. https://doi.org/10.1518/hfes.45.4.635.27088

Winner, H., Hakuli, S., Lotz, F., & Singer, C. (Eds.). (2015). *Handbuch Fahrerassistenzsysteme: Grundlagen, Komponenten und Systeme für aktive Sicherheit und Komfort [Manual Driver Assistance Systems]* (3rd Ed.). Wiesbaden: Springer Vieweg.

Wogalter, M. S., DeJoy, D. M., & Laughery, K. R. (1999). Organizing Theoretical Framework: A Consolidated Communication-Human Information Processing (C-HIP) Model. In M. S. Wogalter, D. DeJoy, & K. R. Laughery (Eds.), *Warnings and Risk Communication* (pp. 13–22). Philadelphia: Taylor & Francis.

Wogalter, M. S., Brelsford, J. W., Desaulniers, D. R., & Laughery, K. R. (1991). Consumer Product Warnings: The Role of Hazard Perception. *Journal of Safety Research*, *22*(2), 71–82. https://doi.org/10.1016/0022-4375(91)90015-N

Woods, D. D. (1995). The Alarm Problem and Directed Attention in Dynamic Fault Management. *Ergonomics*, *38*(11), 2371–2393. https://doi.org/10.1080/00140139508925274

Yamada, K., & Kuchar, J. K. (2006). Preliminary Study of Behavioral and Safety Effects of Driver Dependence on a Warning System in a Driving Simulator. *IEEE Transactions on Systems, Man, and Cybernetics*, *36*(3), 602–610. https://doi.org/10.1109/TSMCA.2006.871646

Zarife, R. (2014). Integrative Warning Concept for Multiple Driver Assistance Systems (Doctoral Dissertation). Julius-Maximilians-University Würzburg. Retrieved from urn:nbn:de:bvb:20-opus-101118

Zhang, Z., Zyphur, M. J., & Preacher, K. J. (2009). Testing Multilevel Mediation Using Hierarchical Linear Models: Problems and Solutions. *Organizational Research Methods*, *12*(4), 695–719. https://doi.org/10.1177/1094428108327450

Zunino, A., Cavazza, J., Koul, A., Cavallo, A., Becchio, C., & Murino, V. (2017). Predicting Human Intentions from Motion Cues Only. In Q. Liu, R. Lienhart, H. Wang, Chen, S. Boll, P. Chen,. . . S. Yan (Eds.), *Proceedings of the 25th ACM international conference on Multimedia Pages* (pp. 591–599). Mountain View, California, USA. https://doi.org/10.1145/3123266.3123298