

# **Towards the Adaptation of Warning Driver Assistance: Behavioral Effects and Implications**

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**Katharina Nora Charlotte Reinmüller**

**aus Würzburg**

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Referent: Prof. Dr. Marco Steinhauser

Korreferentin: Prof. Dr. Andrea Kiesel

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## **Abstract**

Today, vehicles already include a wide range of advanced driver assistance systems (ADAS), which will be further developed to specifically address driver needs. Adaptive ADAS present a new form of driver assistance that is based on driver monitoring algorithms and adjusts system parameters according to the driver's predicted need for support. While it has been suggested that such adaptive systems will improve driving safety and system acceptance, the actual impact of adaptive ADAS on driver behavior and performance remains unclear.

Three studies were carried out to gain knowledge about the potential of adaptive ADAS to minimize the effects of distracted driving while also considering potential adverse behavioral adaptation effects associated with system use. Therefore, this thesis suggests an approach for adaptive forward collision warning (FCW) systems that change warning timing or warning modalities according to driver distraction. Study 1 investigated driver reactions to failures of generic adaptive warning strategies while further examining the influence of awareness on the development of adverse behavioral adaptation. Study 2 extended the approach to a more realistic context and investigated driver reactions to failures of a realistic distraction adaptive FCW system that adjusted warning modalities according to driver distraction in imminent collision situations using a driving simulator. Finally, Study 3 focused on the potential of a distraction adaptive FCW system to induce other forms of adverse behavioral adaptation in terms of riskier driving behavior and increased secondary task engagement. Moreover, in contrast to the previous studies, the presented adaptation strategy in Study 3 was based on a real-time distraction detection algorithm.

In sum, the studies of this doctoral thesis suggest that adaptive FCW systems are generally accepted and have the potential to minimize deficits associated with driver distraction. However, adaptive technologies were found to induce adverse behavioral adaptation in drivers when explicit awareness of system functioning is given. Results demonstrate clear performance and safety impairments for situations in which the adaptive warning strategy fails to present the expected high support. Furthermore, findings show that the mere anticipation of using a distraction adaptive FCW system can adversely affect driving performance. The thesis contributes to traffic research as it provides systematic empirical evidence for the effects of adaptive warnings on driving performance and safety. Both practical implications for the design of adaptive FCWs and methodological implications for future investigations of adaptive technologies based on driver monitoring are discussed.

## **Acronyms**

ABS Anti-lock Braking System

ACC Adaptive Cruise Control

ADAS Advanced Driver Assistance Systems

AIDE Adaptive Integrated Driver-vehicle Interface

BA Behavioral Adaptation

BRT Brake Reaction Time

ESC Electronic Stability Control

FCW Forward Collision Warning

HMI Human Machine Interface

ISO International Organization for Standardization

IVIS In-vehicle Information Systems

LDW Lane Departure Warning

NHTSA National Highway Traffic Safety Administration

OECD Organization for Economic Co-operation and Development

RSVP Rapid Serial Visual Presentation

RT Response Time

SEEV Saliency Effort Expectancy Valence

THW Time Headway

TTC Time to Collision

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## Introduction

From a psychological perspective, driving is a highly complex cognitive every-day task (Groeger, 2000) that comprises a huge number of separate hierarchical subtasks (e.g., Allen, Lunenfeld, & Alexander, 1971; Gibson & Crooks, 1938; McRuer, Allen, Weir, & Klein, 1977; Michon, 1985; Rasmussen, 1986; Walker, Stanton, & Young 2001) and involves both automatic perceptual and cognitive processes (Rumar, 1988). “In driving an automobile, for example, one does not respond randomly to stimuli on the road. Instead, one makes responses in accordance with some internal model which involves reaching a destination at a certain time while obeying various traffic regulations, accommodating oneself to the other traffic on the road, and adapting one’s driving in numerous other ways to the immediate environmental situation” (Fitts & Posner, 1967, p. 3). Taken together, drivers simultaneously stabilize the vehicle on the road by continuously adjusting lateral and longitudinal control, prepare and execute maneuvers such as overtaking and make strategic trip decisions that include route choice and navigation. Therefore safe driving generally depends on the driver’s abilities to meet the driving task demands in a dynamically changing environment (Fuller, 2000, 2005; Fuller & Santos, 2002). The fact that an optimal match between driver abilities and the current task demands is not generally given is reflected in crash data, which shows that still 35,000 people in the US lost their lives in road crashes in 2015 (National Center for Statistics and Analysis, 2016). While task demands may vary according to factors such as sight, weather conditions or vehicle performance, naturally, task capability varies on an interindividual and intraindividual level (Fuller, 2000; Brookhuis & De Waard, 2001). Recent results from naturalistic driving studies, which have observed a large set of potential risk factors for severe crashes, highlight the detrimental impact of driver related aspects (accounting for 94% of crashes) over environmental aspects (accounting for 2% of crashes; Singh, 2015) and identified driver distraction as main risk factor for crashes (e.g., Dingus et al., 2016). Distraction adaptive advanced driver assistance systems (ADAS) adjust system behavior according to whether the driver is distracted from driving or not. By providing distracted drivers with tailored assistance, they present a promising approach to mitigate adverse effects of driver distraction and are likely to be further introduced into the market.

The following empirical test track and driving simulator studies aim at understanding how drivers will use distraction adaptive ADAS. Next to the potential of adaptive warning signals to provide optimized support by facilitating distracted drivers, there is the risk of adverse

behavioral adaptation effects to arise. By estimating the various forms in which potential adverse behavioral adaptation effects could manifest themselves, I intend to gain insight into the complex interaction between the driver and newly introduced technology. While it is prudent to generally gain a more detailed understanding on influential factors for adverse behavioral effects, I also identify factors that can be influenced by system design. Based on a systematic evaluation of adaptive warning signals, I intend both, to inform recommendations that can be applied in the future development of more accepted and safer ADAS and to provide methodological considerations for the research of adaptive ADAS.

## **Conventional advanced driver assistance systems**

In the following section I will give an overview on existing ADAS and common classifications. As this thesis specifically addresses the development of adaptation strategies for warning signals while focusing on forward collision warning (FCW) systems, I will then describe the aims and the functioning of conventional FCW systems. Subsequently I will discuss both the safety potential as well as possible limitations of such systems. The discussed limitations may serve as a starting point for the development of adaptive FCWs.

### **Classification**

Advanced driver assistance systems are in-vehicle technologies which aim at making driving safer and more efficient by supporting drivers in the driving task. For this reason, the development and integration of such systems into vehicles is subject to constant growth (Grand View Research, 2018). While driving, drivers are exposed to a huge amount of information at a time, which have to be processed and integrated in order to make decisions and to generate actions on different levels. According to Donges (1982, 2009) and Michon (1985), the task of driving can be described in terms of three hierarchically organized levels. The control or stabilization level comprises short-term action patterns of vehicle operation that are largely automatized, such as braking. The maneuver or guidance level comprises tasks that are commonly associated with vehicle control and maneuver execution in order to meet the situation's requirements, such as obstacle avoidance, overtaking or turning. On the strategic or navigation level, drivers are concerned with making decisions about forward-looking goals, such as selection of routes, navigation or timing. The levels differ according to their functionality and the timescales, in which the involved tasks are executed (Michon, 1985). While the operational tasks are executed in units of milliseconds, maneuver execution can last



multiple seconds and strategic plans have long time horizons. Since assistance in the form of ADAS is able to influence all levels of the driving task, the hierarchical three-level structure has been adapted by Freymann’s (2006) classification of ADAS. It describes ADAS according to the supported level of the driving task, the associated system timescales and the safety relevance. The classification of common ADAS including adaptive cruise control (ACC), FCW systems or lane departure warning (LDW) systems is presented in Figure 1.

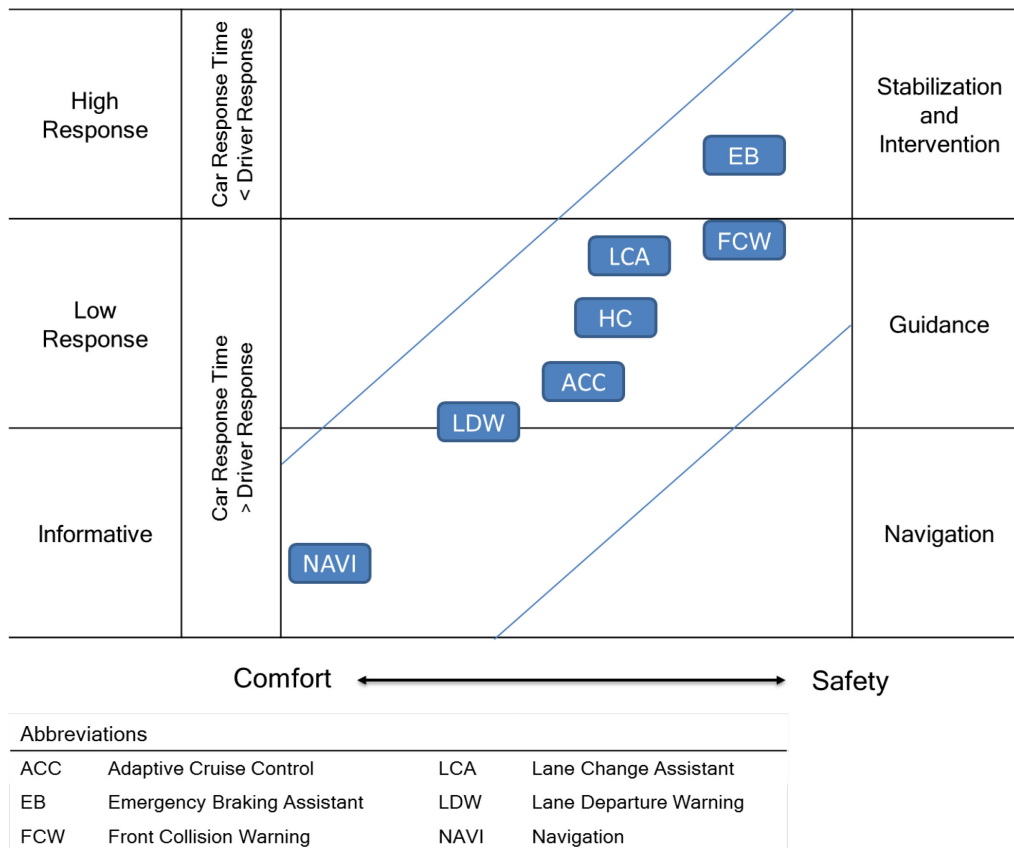


Figure 1. Categorization of common advanced driver assistance systems according to Freymann (2006). Adapted from Freymann (2006) and Zarife (2014).

In a different approach of ADAS classification, Gasser, Frey, Seeck, and Auerswald (2017) specifically address the driver’s responsibilities regarding the execution of the driving task while interacting with an ADAS. They argue that ADAS can support the driver either indirectly by providing him with driving-relevant information or directly by taking vehicle control in various ways. The conclusive classification of ADAS by Gasser et al. (2017) specifically focuses on functions influencing vehicle guidance and categorizes functions by three operation principles: (1) informing and warning, (2) continuously automating, and (3) temporarily intervening. Informing and warning functions enhance the driver’s perception by

communicating driving-relevant information that is presented either inside or outside the vehicle. They thus influence driving behavior indirectly by providing status information and warnings to direct the driver's attention to either an abstract or concrete hazard. Current examples of informing systems are traffic light assistants, night vision or traffic sign detection. Warning functions may warn against critical scenarios (e.g., LDW, blind spot detection). Even though these functions prepare drivers to make efficient decisions, it is up to the drivers alone whether and how they use presented warnings and information. In contrast, there are two categories of functions that directly influence vehicle control. First, continuously automating ADAS take over either lateral (lane keeping assistance) or longitudinal (ACC) vehicle control of the driving task for a longer period of time. Second, temporarily intervening ADAS automatically intervene only in critical accident-prone situations. For example, autonomous braking systems automatically decelerate when they identify a high risk of colliding with a vehicle or road user. Importantly, according to the presented classification, functions that provide haptic-kinesthetic signals in form of brake jerks that produce a short, noticeable deceleration may not be considered as classical warning functions as in contrast to different forms of non-intrusive visual, acoustic and haptic signals they temporarily intervene in vehicle control. However, it should be noted that brake jerks are usually considered warning signals that aim to attract the driver's attention and promote braking reactions (e.g., Campbell, Richard, Brown, & McCallum, 2007; Kiefer, 2000; Kiefer et al., 1999; Maier, Hellbrück, & Sacher, 2014).

### **FCW systems**

Rear-end collisions are the most prevalent crash type representing 32% of all crashes and being the crash type associated with most injuries in the US in 2013 (National Highway Traffic Safety Administration [NHTSA], 2015). Interestingly, driver distraction and inattention occurred more often in rear-end crashes than in other crash types and played a role in 40-93% of rear-end crashes (Dingus et al., 2006; McEvoy, Stevenson, & Woodward, 2007). FCW systems aim to prevent such rear-end collisions by alerting the driver, e.g., in form of auditory (Baldwin & May, 2011; Cheng, Hashimoto, & Suetomi, 2002; McGehee, Brown, Lee, & Wilson, 2002) or visual warnings (e.g., De Rosario et al., 2010), when a critical situation is detected in the path of the vehicle. Some concepts have also considered haptic warnings in form of brake jerk warnings, which trigger a short burst of deceleration in order to alert the driver (e.g., Lerner et al., 2011; Lubbe, 2017; Tijerina et al., 2000). Accordingly, the primary focus of

FCW systems is to reduce the incidents of rear-end collisions with other vehicles, bicycles and pedestrians by facilitating the driver to attend to the critical event in response to the warning. Conventional FCW systems are warning functions that have an indirect effect on safety, i.e., they draw attention to the critical driving situation while the driver is in full responsibility for braking (Gasser et al., 2017, see section “Classification”). FCW algorithms typically consider fixed threshold values to trigger warnings based on physical measures of the situation such as the time to collision (TTC) between the vehicle and the leading vehicle or the minimum distance required to safely stop the vehicle in case the leading vehicle decelerates at a maximum (Bella & Russo, 2011).

FCW systems have been introduced to the US market by auto manufacturers in 2000 and steadily improved over the years (Cicchino, 2017). FCW systems have been revealed to be effective in different aspects by studies that investigated driver performance and collisions in situations with collision warnings and compared them with situations without any warning (e.g., Baldwin & May, 2011; Cicchino, 2017; Gray, 2011; Ho, Reed, & Spence, 2006; Lee, McGehee, Brown, & Reyes, 2002; Maltz & Shinar, 2004). Moreover, Kusano and Gabler (2012), who tested the effectiveness of FCW algorithms in simulated real-world crashes, found a clear prevention potential regarding the number of collisions and seriously to fatally injured drivers. Nevertheless, warning systems are suggested to be faced with the classical warning dilemma in both parameters warning timing (e.g., Abe & Richardson, 2006; Brown, Lee, & McGehee, 2001; Janssen, Alm, Michon, & Smiley, 1993; Lee et al., 2002; Smith, Witt, Bakowski, Leblanc, & Lee, 2009) and warning characteristics (Smith et al., 2009), which makes it difficult to provide optimal support to both distracted and undistracted drivers.

The warning timing dilemma addresses the trade-off between an early intervention and the experience of false alarms. Empirically, studies addressing the effect of warning timing on collision behavior suggest that warning effectiveness can be maximized by earlier alarms as drivers usually react faster (Abe & Richardson, 2004; Lee et al., 2002; McGehee et al., 2002) and experience less collisions (Lee et al., 2002; McGehee et al., 2002). Providing sufficient time to react to a critical event is especially important for distracted drivers who generally show response time (RT) deficits (see e.g., Alm & Nilsson, 1995; Hancock, Lesch, & Simmons, 2003; Lee et al., 2002; Reed & Robbins, 2008; Salvucci & Beltowska, 2008; Strayer, Drews, & Johnston, 2003) and are more prone to vehicle crashes (Dingus et al., 2006, 2016; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; Olson, Hanowski, Hickman, & Bocanegra, 2009). It therefore may be relevant to provide support that specifically addresses the need of distracted

drivers and compensates for their deficits. However, earlier warning signals are associated with more insecurities about the actual criticality of the situation which may lead to the frequent output of false signals or the feeling of nuisance (e.g., Abe & Richardson, 2004; Janssen et al., 1993; McGehee et al., 2002) as drivers are likely to appropriately respond to the situation on their own (Carsten, 2005; Donmez, Boyle, & Lee, 2007). The presentation of frequent false alarms can in turn lead to a cry-wolf effect (Breznitz, 1983): Decreased willingness to react to an alarm due to prior experience of false alarms and associated loss of the alarm's credibility. Indeed, frequent false alarms may be associated with decreased system compliance (Abe, Itoh, & Tanaka, 2002; Bliss & Acton, 2003; Cotté, Meyer, & Coughlin, 2001; Lees & Lee, 2007; Yamada & Kuchar, 2006), irritation (Lind, 2007) and acceptance problems (Kidd, Cicchino, Reagan, & Kerfoot, 2017; Ervin et al., 2005; Sorkin, 1988; Tijerina, Hendricks, Pierowicz, Everson, & Kiger, 1993). In standard warning systems, such as FCWs support may be perceived as inappropriate when it does not match the criticality of the situation (Abe & Richardson, 2004; Carsten, 2005). A field operational test found that nearly one third of drivers would have chosen to switch off a tested FCW system, if it had been possible due to the feeling of nuisance (Ervin et al., 2005). According to the problems associated with early alarms, research recommends using rather late alert timings for imminent collision warnings (Hoffmann & Gayko, 2009; Huey, Harpster, & Lerner, 1997; Kiefer, 2000; Lee et al., 2002). Interestingly, later alert timings with average TTC thresholds of approximately 2.3 seconds also represent the common configuration of collision warning systems on the market (Forkenbrock & O'Harra, 2009; Kusano & Gabler, 2015). This may explain why FCWs are widely accepted by drivers, which is demonstrated by different studies showing that if the vehicle is equipped with FCW technologies, it is used by over 90% of drivers (Reagan, Cicchino, Kerfoot, & Weast, 2018; Reagan & McCartt, 2016) and turned on 91% of the driving time (Flanagan et al., 2016).

Crucially, next to warning timing, also warning characteristics may influence safety and acceptance. Studies showed that urgent warnings have the potential to provide efficient support as they generally induce quick responses (e.g., Cao, van der Sluis, Theune, op den Akker, & Nijholt, 2010; Edworthy, Hellier, Walters, Weedon, & Adams, 2000; Haas & Cassali, 1995; Naujoks, Kiesel, & Neukum, 2016; Tan & Lerner, 1995). However, urgent signals were also found to be associated with perceived annoyance (Baldwin & May, 2011; Tan & Lerner, 1995; Wiese & Lee, 2004) especially in situations where urgent warnings are considered less appropriate (Marshall, Lee, & Austria, 2007). In line with this, Politis, Brewster, and Pollick (2013) were able to show that multimodal warnings, which elicited faster responses, were also associated with higher perceived urgency and annoyance, which could possibly undermine

system acceptance. It is further suggested that too intensive warnings may induce adverse effects in form of startle responses (Bliss & Acton, 2003; Dingus et al., 1997; Edworthy, 1994; Kircher & Ahlstrom, 2013), confusion and improper reactions (Bliss & Acton, 2003; Kircher & Ahlstrom, 2013). Startle responses were found to be especially likely in false alert situations (Ervin et al., 2005).

In sum, research on FCW systems demonstrated that those systems are used frequently that are able to defuse critical situations and thereby increase safety. At the same time, the warning dilemma between the presentation of early/ urgent warnings and the presentation of late/ less intrusive warnings still plays a huge role in the concrete design of current FCW algorithms. It remains to be investigated to which extent adaptation strategies by means of adjusting warning parameters to the distracted driver's need for support may be able to overcome this problem.

## **Driver distraction**

The following chapter provides insights into empirical research and theoretical background related to driver distraction. Specific deficits and risks associated with distraction may have implications for the distracted driver's specific needs that in turn could be addressed by distraction mitigation approaches such as adaptive ADAS.

### **Empirical studies on distracted driving**

While there is no consent on a definition of driver distraction (e.g., Lee, Young, & Regan, 2008; Pettitt, Burnett, & Stevens, 2005; Regan, Hallett, & Gordon, 2011), Lee et al. (2008) developed a comprehensive definition that understands driver distraction as the "diversion of attention away from activities critical for safe driving toward a competing activity" (Lee et al., 2008, p. 34). Accordingly, distraction can be considered a specific form of inattention that manifests itself in different non-driving-related behaviors such as interacting with a passenger, mind-wandering, in-vehicle information systems (IVIS) or cell-phone use. With rapidly evolving technologies such as smart phones, wearable devices and advanced in-vehicle applications, steadily new distraction sources are developing and pose a significant safety concern.

Throughout the literature, driver distraction is reported to be a major factor in impaired driving. Research of the last 20 years has clearly established that driver distraction impairs

driving performance with important findings stemming from research on cell-phone usage and cognitive distraction during driving. This research was able to show that such distractions impair the primary task of driving as they lead to impairments in situation awareness (e.g., Gugerty, Rakauskas, & Brooks, 2004; Kass, Cole, & Stanny, 2007; Ma & Kaber, 2005) visual attention (e.g., Atchley & Dressel, 2004; Desmet & Diependaele, 2019; Harbluk, Noy, Trbovich, & Eizenman, 2007; McCarley et al., 2004; Strayer & Drews, 2007; Strayer et al., 2003), RT (e.g., Alm & Nilsson, 1995; Consiglio, Driscoll, Witte, & Berg, 2003; Hancock et al., 2003; Salvucci & Beltowska, 2008; Strayer et al., 2003; for a review, see Morgan et al., 2011) as well as driving performance (Alm & Nilsson, 1995; Harbluk et al., 2007; Kass et al., 2007; Salvucci & Beltowska, 2008; for a meta-analysis, see Horrey & Wickens, 2006; for a recent meta-analysis, see Caird, Simmons, Wiley, Johnston, & Horrey, 2018).

Additional experimental research has revealed adverse effects on driving due to eating (e.g., Alosco et al., 2012; Irwin, Monement, & Desbrow, 2015; Jenness, Lattanzio, O'Toole, & Taylor, 2002), texting (e.g., Alosco et al., 2012; Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; He, Chaparro, et al., 2014; Irwin et al., 2015; Reed & Robbins, 2008; Rumschlag et al., 2015), using IVIS (e.g., Lee, Caven, Haake, & Brown, 2001; Merat & Jamson, 2008) as well as internal distractions such as emotions (Jeon, Walker, & Yim, 2014; Jones, Chapman, & Bailey, 2014) or mind-wandering (Yanko & Spalek, 2014). It is difficult, however, to infer the contribution of the widely reported deficits in distracted driving to crash risk (McEvoy et al., 2007) and real-world safety. Research on the effects of distracted driving provides two implications. First, it shows that driver distraction may impair different stages of information processing in driving. Second, it demonstrates that the detrimental effects of distraction are not restricted to specific types of non-driving-related tasks and thus forms of distraction, as deficits can be found for tasks that impose all three forms of distraction, namely cognitive, visual and manual distraction. However, executing primarily cognitive tasks while driving may be associated with differential impairments than executing primarily visual tasks. For example, visual distraction was found to result in impairments in lane keeping (e.g., Engström, Johansson, & Östlund, 2005; Peng, Boyle, & Hallmark, 2013; Santos, Merat, Mouta, Brookhuis, & De Waard, 2005), while studies typically found no such effects for cognitive distraction imposed by hands-free telephone conversations or working memory tasks (e.g., Alm & Nilsson, 1995; Brookhuis, de Vries, & de Waard, 1991; Engström et al., 2005; He, McCarley, & Kramer, 2014; Rakauskas, Gugerty, & Waard, 2004; for a review, see Engström, Markkula, Victor, & Merat, 2017). However, both visual (Lee et al., 2002; Olsson & Burns, 2000) and cognitive distraction (Alm & Nilsson, 1995; Gugerty et al., 2004; Olsson & Burns, 2000;

Strayer & Johnston, 2001) resulted in delayed or missed responses to hazards and signals, which thus presents a common deficit of distraction. Accordingly, distraction mitigation strategies such as adaptive ADAS may distinguish different forms of driver distraction while specifically taking into account the need for support associated with their occurrence.

The actual impact of distraction on real-world driving safety is revealed by both epidemiologic crash data investigations (e.g., Beanland, Fitzharris, Young, & Lenné, 2013; McEvoy et al., 2007) and naturalistic driving studies (e.g., Carney, McGehee, Harland, Weiss, & Raby, 2015; Dingus et al., 2006, 2016; Klauer et al., 2006; Olson et al., 2009; Singh, 2015), which generally focus on three important measures: the severity of crashes associated with distraction, the overall crash risk associated with it and the prevalence of driver distraction. Observational studies provide an unambiguous picture of the detrimental impact of distraction and inattention on crashes, as they were generally identified a contributing factor in 68 to 78% of all crashes (Dingus et al., 2006, 2016; Klauer et al., 2006; Olson et al., 2009). In contrast, self-reports seem to underestimate this effect as only 33% of drivers reported to have executed a distracting activity at the moment of the incident (McEvoy et al., 2007). Importantly, glancing away from the road was identified as a major risk factor since naturalistic driving has revealed average glance-off-the-road times of 1.8 seconds before crashes (Klauer et al., 2006). It is also noteworthy that Dingus et al. (2016) found that drivers were involved in some kind of observable distracting activity in over 50% of the time, which was associated with a two times higher risk for a severe crash with the most prevalent activity being the interaction with passengers, followed by handheld cell-phone use and IVIS interaction. Looking at the specific forms of distraction, the crash risk was found to be especially high for complex non-driving related tasks such as texting or phone dialing (e.g., Dingus et al., 2016; Olson et al., 2009), which can be regarded critically as over 47% of adult drivers report to have texted while driving (Madden & Rainie, 2010). When considering the severity of crashes, statistics revealed that almost 3500 people died in crashes caused by driver distraction in the US in 2015. Thus, distraction accounted for nearly 10% of all road crash fatalities (National Center for Statistics and Analysis, 2016). It is further suggested that drivers mostly actively decide to disengage from driving (Horrey & Lesch, 2009; Lee, Regan, & Young, 2008), which is supported by the finding that approximately 70% of assessed forms of distraction were voluntarily initiated by the driver (Beanland et al., 2013). In sum, different forms of driver distraction negatively influence driving performance and have detrimental effects on crash risk, which highlights the need of distraction mitigation.

### Theories of driver distraction

The presented findings demonstrate that distracted driving may lead to a break-down of performance and safety. Impaired performance in driving situations can be explained by different theories of central information processing. First, drivers may fail to remain focused on driving-relevant stimuli within the vehicle and driving environment. Traditional theories of selective attention assume that the attentional system is limited in the amount of information that can be processed at a given time (Broadbent, 1958; Deutsch & Deutsch, 1963; Norman, 1968; Treisman, 1964). Given the prediction that individuals must filter information selectively because they are unable to process a large amount of sensory information at a time, input is filtered. However, the selection process was considered to take place at different stages of information processing. On the one hand, selection is considered to take place at an early stage of processing based on an analysis of the input's perceptual characteristics before it reaches conscious awareness (Broadbent, 1958; Treisman, 1964). On the other hand, information processing is considered to be limited by post-perceptual bottlenecks, i.e., serial processing happens based on the semantic content at the response selection stage (Deutsch & Deutsch, 1963; Norman, 1968).

Second, driving performance decrements may stem from the concurrent engagement in a non-driving related secondary task. Such dual-task inferences can be attributed to a central bottleneck (Pashler, 1984, 1994; Pashler & Johnston, 1989; Welford, 1952), which postulates that it is impossible to execute two or more central operations at a time. Support for this central bottleneck is also provided by simulated driving research (Levy & Pashler, 2008; Levy, Pashler, & Boer, 2006). For example, Levy et al. (2006) found increased RTs in a braking task when the time interval between a lead-vehicle brake stimulus and a previously presented stimulus of an additional task was reduced.

As a competing theoretical approach to the central bottleneck in information processing, capacity models of attention propose that dual-task inferences result from a limited resource or capacity (Kahneman, 1973; Moray, 1967; Navon & Miller, 2002; Norman & Bobrow, 1975; Tombu & Jolicœur, 2003). As predicted by Kahneman (1973) mental capacity may be variable depending on factors such as the level of arousal, while task demands on processing capacity vary according to both its nature and prior experience with it. In general, available capacity can be allocated to different tasks concurrently. When the amount of capacity needed to execute one or more tasks exceeds the currently available capacity supplied by the single resource, interference by means of performance decrements and response delays is predicted. This



implies that parallel task performance is possible as long as capacity is not exceeded. Importantly, Kahneman's theory suggests that attention allocation is determined by enduring dispositions and momentary intentions. Other than single capacity models, multiple resource theories (Navon & Gopher, 1979; Wickens, 1980, 1984, 2002, 2008) suggest that attentional processes rely on a number of multiple resources. A model widely-used in applied research is Wickens' (1980, 1984, 2002, 2008) model of multiple resources. It generally considers separate resources for the processing stages perception, cognition and response selection. Importantly, Wickens further distinguishes between separate auditory and visual resources within perception and separate manual and vocal responses within response selection. In multiple resource theory, the degree of similarity of the concurrently performed tasks determines dual-task performance as disruptions or interferences are expected to increase by the extent to which tasks compete for the same resources. Moreover, performance may decrease with overall task difficulty and thus resource demands. This theory is supported by research showing more interference for stimuli with shared input modalities compared to stimuli with different modalities (e.g., Treisman & Davies, 1973). Moreover, the model was successful in predicting interference in driving (e.g., Horrey & Wickens, 2004).

While both theories of selective attention as well as dual-task paradigms can account for findings on distracted driving, the transfer to real-world attention allocation and thus dynamical and complex situations like everyday natural driving is difficult as the complex interplay between bottom-up influences and top-down goals, that was demonstrated in various studies (e.g., Shinoda, Hayhoe, & Shrivastava, 2001; Summala & Hietämäki, 1984), is not fully considered. Drivers tend to automatically allocate their attention to salient information such as an abruptly appearing warning while also focusing on their goals, e.g., by voluntarily allocating attention to gaps when choosing to change lanes. With regard to driver distraction, Horrey and Lesch (2009), Lee, Regan, and Young (2008) and Lerner (2005) argue that drivers are not passively committed to distraction, but voluntarily chose to attend to non-driving related tasks while driving. This view is in line with findings from real-world driving (Beanland et al., 2013; Dingus et al., 2016) demonstrating that voluntarily distraction including interacting with a passenger or using in-vehicle devices can be considered a very common type of distraction. Moreover, self-reports (e.g., Young & Lenné, 2010) and real-world observations (e.g., Tivesten & Dozza, 2015) imply that drivers actively decide whether and when to engage in secondary tasks and thus adapt their behavior according to situational demands. A model that considered both goal-directed and stimulus-driven components of attention was proposed by Wickens, Helleberg, Goh, Xu, and Horrey (2001). Their SEEV model predicts visual attention allocation

within the scene based on different factors, such as saliency, effort, expectancy, and value. Both saliency (which includes stimulus characteristics) and effort (which refers to physical effort associated with attention allocation) are defined as bottom-up parameters. In contrast, expectancy and subjective value of information and tasks are defined as top-down factors. The probability of attending to a specific area within the scene is calculated by comparing the different input parameters. Empirical research has successfully applied the SEEV model to driving (Horrey, Wickens, & Consalus, 2006) and flying applications (Wickens, Goh, Helleberg, Horrey, & Talleur, 2003). While the model may provide a useful framework for the prediction of sequential visual scanning behavior, it is restricted. As noted by Engström, Victor, and Markkula (2013) it cannot account for dual-task costs and does not consider other forms of attention allocation.

Taken together, different psychological models may account for driving performance decrements associated with driver distraction. In sum, driver distraction may be understood as to be determined by (1) serial processing (bottleneck models), (2) task demands exceeding the resources of the single pool (single capacity models), or concurrently performed tasks demanding overlapping resources (multiple resources). Importantly, the identified limitations of human information processing may provide implications as to how the interaction between vehicle and driver, especially with regard to adaptive ADAS, has to be designed. For example, in order to be processed adequately, warnings should have high sensory salience and intuitively convey relevant information. The presented information should be easy to understand in order to prevent additional demands that may impair the driver's response to it. Another implication is that warnings should make use of different pools of resources than the driving and distraction task, e.g., by choosing a different sensory modality or a different type of required response.

## Using adaptation to mitigate effects of driver distraction

In the following chapters, I will provide a definition of adaptive ADAS in the context of driver distraction. As the thesis focuses on adaptive FCWs, I will present and categorize a range of adaptation strategies that can be used for adaptive warning functions and FCWs in particular. Furthermore, I will give a short overview of experimental studies on different types of adaptive ADAS. Subsequently, the major technical and human factor challenges in the development of distraction adaptive warning functions will be discussed. Importantly, as studies on effective adaptive warning functions are rare, findings on conventional warning functions may serve as a starting point for the design of warnings that specifically address distracted drivers' needs. Thus, potential ways to overcome challenges in development of distraction adaptive warning functions are discussed in consideration with conventional warning research.

### Adaptive ADAS

#### *Definition and functioning of adaptive ADAS*

Given that distracting activities are so common during driving, Lee (2014) suggested to consider distracted driving as normal baseline behavior. Following this argumentation, it is relevant to provide support that specifically addresses the need of distracted drivers and compensates for their deficits. Consequently, different forms of distraction mitigation strategies have been proposed (for overviews, see Donmez, Boyle, & Lee, 2003; Donmez, Boyle, Lee, & McGehee, 2006; Engström & Victor, 2009; Kircher & Ahlstrom, 2013). Generally, driver mitigation strategies can be divided into strategies that aim at preventing distraction and strategies that aim at mitigating adverse effects of distraction on driving performance and safety by compensating for distraction-induced deficits in drivers (Engström & Victor, 2009). Among strategies that focus on the prevention of distraction are warning systems that provide distraction alerts (e.g., Ahlstrom, Kircher, & Kircher, 2013; Kircher, Kircher, & Ahlstrom, 2009), workload managers that suppress incoming calls or interrupt IVIS tasks according to the expected workload level of the driver (e.g., Piechulla, Mayser, Gehrke, & König, 2003; Tijerina et al., 2011; for a review, see Green, 2004), and feedback systems that give either direct or retrospective feedback on the driver's attentional state (Donmez et al., 2007; Donmez, Boyle, & Lee, 2008). An alternative approach to address driver distraction using driver assistance is not to warn of distraction, but to dynamically adjust system behavior according to the current driver state while considering the driver's needs for assistance to enhance safety and acceptance

(e.g., Blaschke, Breyer, Färber, Freyer, & Limbacher, 2009; Hajek, Gaponova, Fleischer, & Krems, 2013). That way, adaptive systems aim at mitigating the adverse effects of distraction by providing user-centered assistance.

Distraction adaptive ADAS are based on the idea that drivers' needs for support may change during driving as their degree of distraction changes, e.g., due to cognitive, manual or visual involvement in a concurrent activity. As a consequence, such systems continuously monitor the driving environment as well as the driver for critical states by using technologies such as eye-trackers or camera sensors. In case of a safety-critical driving situation such as an upcoming collision is detected, an adaptive system automatically integrates the distraction information and adjusts system parameters to support the driver according to his needs. That way, adaptive ADAS should improve human–vehicle interaction.

According to Smith et al. (2009), adaptive warnings could be useful as they solve the warning dilemma between acceptance and safety (see chapter “FCW systems”) by two forms of adaptation. Positive adaptation refers to providing increased support to currently distracted drivers to promote safer driving, while negative adaptation refers to the attenuation of support in currently undistracted drivers to reduce annoyance and thus promote acceptance. From the perspective of regulating the impact of driver distraction, adaptive warning systems should be able to compensate for the deficits associated with driver distraction and thus minimize performance and safety differences between distracted and undistracted drivers.

In the context of warning functions, there are two primary ways in which a system can adjust to the driver's needs, namely human machine interface (HMI)-based and algorithm-based adaptation strategies (Smith et al., 2009). Using an HMI-based strategy, a warning system dynamically adjusts interface features and thus alters the way drivers perceive the warnings. Examples for such adaptation strategies are adapting the modality in which the warning is presented, the intensity of warning parameters, or the location of warning presentation. Algorithm based strategies modify warning triggering themselves and comprise both the adaptation of the time at which a warning is initiated and warning presentation itself. Table 1 presents an overview of adaptive warning strategies.

**Table 1.** Integrative overview of adaptation strategies for warning functions (adapted from Smith et al., 2009)

|                 | Adaptation strategy | Concrete manifestation of changes when distraction is detected |
|-----------------|---------------------|--|
| HMI-based       | Modality            | Change modality<br>Add modality/ modalities                    |
|                 | Intensity           | Vary parameters of presented modality                          |
|                 | Location            | Change location<br>Add location<br>Add direction               |
| Algorithm-based | Timing              | Present warning earlier  |
|                 | Suppression         | Present warning  |

Research is required to increase our insight into whether and to what extent these adaptation strategies are able to successfully support performance and safety in distracted drivers through the presentation of user-centered support. Thus, based on findings on the effectiveness of different warning modalities, intensities and timings that were generated regardless of their applicability to adaptive systems, the following section focuses on human factors considerations for warning strategies that may contribute to the identification of promising adaptation strategies.

#### *Exemplary studies on adaptive ADAS*

While the adaptation approach was often proposed (e.g., Carsten, 2005; Engström & Victor, 2009; Fernández, Usamentiaga, Carús, & Casado, 2016; Kircher & Ahlstrom, 2013; Lee et al., 2002; Rudin-Brown, 2010), studies on adaptive ADAS are rare and provide an incomplete picture. Studies investigated distraction adaptation in LDWs (Smith et al., 2009), lane keeping assistance (Pohl, Birk, & Westervall, 2007), adaptive cruise control (ACC; Hajek et al., 2013), traffic sign warnings (Fletcher & Zelinsky, 2007) and FCW systems (Smith et al., 2009). In a more recent study by Hajek et al. (2013), an ACC increased the distance to vehicles ahead according to a driver's engagement in an experimentally induced cognitive secondary task to provide a larger safety margin in case the distracted driver has to regain control of the vehicle. Indeed, distracted drivers reacted as fast as undistracted drivers while decelerating less strongly, which was interpreted as increased control of the critical situation. Blaschke et al. (2009) proposed an adaptive lane keeping assistance. They tested to what extent distracted drivers benefit from differentially timed steering torque interventions. Crucially, deficits in lane keeping performance observed during unassisted, distracted driving were compensated using

continuous and early torques. Furthermore, lane keeping performance in assisted, distracted driving did not differ from undistracted baseline driving. While this study could identify assistance that optimally offsets performance impairments due to secondary task engagement, the informative value regarding adaptive ADAS was limited as drivers did not experience system adaptivity. In a similar approach, Pohl et al. (2007) presented a distraction-based lane keeping assistance system based on eye-tracking and head tracking metrics to model driver distraction. However, as the main aim of integrating distraction detection was to reduce the number of false warnings, the system suppressed warnings whenever the driver was detected to be attentive to the roadway at the moment the vehicle departs from the lane. The system was evaluated as useful in reducing the number of false alarm, but the number of situations in which the system failed to present warnings to distracted drivers increased due to inaccuracies in driver detection. Fletcher and Zelinsky (2007) considered eye-tracking and speeding to infer whether drivers had perceived a road sign and adjusted traffic sign warnings accordingly. Only if the driver was predicted to not have realized a sign change, the adaptive system provided respective warnings. While the adaptive warning algorithm showed promising results to warn drivers only when needed, the study provided no measures of performance, safety and acceptance.

Different forms of adaptive warning strategies were implemented in FCW and LDW systems in the AIDE and SAVE-IT projects. The idea of presenting an additional auditory warning component when drivers are distracted from the frontal driving scene and thus may not perceive a visual warning was realized for an FCW system. Results show that compared to unassisted driving, especially the auditory warnings sped up initial reactions and minimized crash risk in distracted, but not in attentive drivers (Smith, Witt, & Bakowski, 2008). In Smith et al. (2009) a location-based adaptation strategy that presented a visual warning component of a visuo-auditory warning signal at the estimated location of visual attention was implemented in both an FCW and LDW. However, this strategy could not improve safety as it prevented distracted drivers from quickly and automatically attending to the critical scenario on the road. Adaptively suppressing visuo-auditory warnings during undistracted driving led to a reduction of alarms relative to a non-adaptive warning strategy which was further accompanied by a decreased feeling of nuisance in FCW systems and increased acceptance and safety ratings in LDW systems. Adaptive FCWs showed promising results for a timing-based warning strategy that presented earlier warnings during distraction situations. Presenting warnings 2 s earlier made distracted drivers react 800 ms faster than the baseline warning.

In sum, previous research proposes the mitigation of distraction effects due to optimized driver support as the main goal of such systems. However, the presented findings also show that not all forms of adaptations are useful. Indeed, so far only one study was able to demonstrate the potential of adaptive warnings to minimize distraction induced deficits in driving performance. Moreover, most studies fail to report both safety and acceptance aspects of the introduced adaptation strategies.

## **Human factors challenges in adaptive warning functions**

### *Warning design*

Adaptive warning systems may account for the urgent need to provide adequate support to distracted drivers who are at risk of driving impairments (e.g., Alm & Nilsson, 1995; Atchley & Dressel, 2004; Desmet & Diependaele, 2019; Gugerty et al., 2004; Hancock et al., 2003; Harbluk et al., 2007; Kass et al., 2007; Ma & Kaber, 2005; McCarley et al., 2004; Strayer & Drews, 2007; Strayer et al., 2003; Strayer & Johnston, 2001) and crashes (Dingus et al., 2006, 2016; Klauer et al., 2006; Olson et al., 2009; Singh, 2015). It therefore raises the question, which modality and timing should be used to effectively support a distracted drivers by reliably capturing their attention. Unfortunately, studies on adaptive ADAS are rare and could not provide sufficient evidence for efficient warning parameters for adaptation strategies. Therefore, considerations for efficient adaptation strategies may be largely based on research on conventional warning functions. Previous research investigated the effect of both warning modalities and warning timings in distracted driving and thus may provide insight into efficient warning design for distracted drivers and thus provide implications for the design of promising adaptation strategies for adaptive ADAS.

With respect to useful warning modalities for distracted drivers, Smith et al. (2009) analyzed visual and visuo-auditory forward collision warnings and compared their effects to unassisted driving. Results show that undistracted drivers generally did not benefit from any warning while drivers who were distracted from the forward scene had decreased crash numbers for visual compared to no warning conditions and least crashes when visuo-auditory warnings were presented. Similarly, RTs were shortest for distracted drivers when they received visuo-auditory warnings. Biondi, Strayer, Rossi, Gastaldi, and Mulatti (2017) studied the utility of different collision warnings in different distraction situations, i.e., with and without hands free phone conversations. Drivers were generally more successful in reacting to the critical front event in a timely manner when they used multimodal warnings compared to auditory, tactile

and no warnings. However, there was no difference in RTs to auditory and tactile signals. Kramer, Cassavaugh, Horrey, Becic, and Mayhugh (2007) investigated the effectiveness of visual and visual-auditory warnings in distracted drivers who engaged in a visual in-vehicle reading task. Warnings were presented in critical lateral and longitudinal scenarios. Irrespective of the scenario, decreased RTs were found for situations in which drivers received visual-auditory warnings compared to when there was no alert. Moreover, the crash rate was lower when drivers received bimodal warnings compared to visual and no warnings. In a study by Mohebbi, Gray, and Tan (2009) the potential of auditory and tactile warnings to prevent collisions with a suddenly decelerating vehicle in the frontal roadway were examined in comparison to a no warning condition. Participants were engaged in either no conversation, simple or complex conversations during driving. Results show a large safety potential for tactile warnings irrespective of the conversation complexity as tactile warnings were able to reduce the adverse effects of distraction on RT. However, contrary to Biondi et al. (2017) providing an auditory warning was not efficient in both conversation situations as it did not lead to shorter RT than no warning. In a further study, Bueno, Fabrigoule, Ndiaye, and Fort (2014) investigated the effects of auditory collision warnings when drivers were engaged in a highly or moderately distracting cognitive task that involved word association and compared them to unassisted, undistracted baseline driving. Moderately distracted drivers largely benefitted from auditory warnings as they initiated faster reactions and kept safer headways than baseline drivers. However, there were no more performance differences for highly distracted drivers relative to the baseline group after an initial critical event. Taken together, warning modality research implies that warning processing relies on available resources and that warning effectiveness is high for multimodal warnings. Moreover, studies indicate that the effectiveness further depends on if and to what extent modalities interfere with the characteristics of the secondary task. The idea of separate attentional resources has been early expressed in multiple resource theory (Wickens, 1980, 1984, 2002, 2008), which suggests that interference occurs when tasks share the same perceptual modalities, processing stages, processing codes or visual channels. Accordingly, when tasks involve different resources there should be no risk of interference and thus performance impairments. Implications of multiple resource theory would be to choose warning modalities that use another input modality than the currently performed task to avoid overloading the driver's attentional resources. Moreover, in line with the redundancy gain phenomenon (Miller, 1982; Raab, 1962), which suggests facilitation of reactions to two targets compared to a single target, presenting redundant warnings in more than one modality may improve perception and thus may be especially useful for currently distracted drivers.



Regarding warning timing, distracted drivers would be expected to react more slowly than undistracted drivers, thus effective warnings for distracted drivers have to be presented earlier to compensate for those deficits. This dependency is considered in the prominent algorithm for rear-end collision warning timing, the start-stop-algorithm (ISO [International Organization for Standardization], 2005), which calculates the warning timing based on driver reactions regarding the expected brake reaction time (BRT) as well as a deceleration estimation. Studies have investigated the positive effect of early warning signals. However, mostly early warning signals were examined in undistracted drivers. In a study by McGeehe et al. (2002), a FCW system warned an undistracted driver about imminent collisions using either early or late warnings based on an RT estimation of 1.5 and 1.0 seconds, respectively, in a car-following scenario. Those two warning groups were compared to a baseline group without any assistance. Both initial driver reactions and severity of the collision were improved using an FCW compared to no assistance. However, the positive effect on those parameters was even more pronounced for the early warning. In a driving simulator study, Abe and Richardson (2004) compared undistracted driver's reactions to early, middle and late alarms that were presented 0.05, 0.64, and 0.99 s after the initiation of a lead vehicle braking respectively. Results indicate that drivers benefited most from early alarms as they lead to shorter accelerator pedal release times. However, the authors state that for warning design the middle alarm may be the most useful as it presents a compromise between efficiency and annoyance potential, which may be high for early alarms when they are perceived as nuisance. Lee et al. (2002) compared different FCW timings to a baseline drive without assistance. In their simulator study, drivers were warned using an icon together with a warning tone either early (assumed RT = 1.5 s) or late (assumed RT = 1.0 s) in situations in which a lead-vehicle suddenly decelerated differentially strong. They found that warnings were generally useful as warning drives relative to baseline drives were associated with less crashes, reduced crash severity and faster initial responses to the threat. This was particularly true for warnings that were provided early. In a further experimental session using the same warning specifications, the authors were able to show that both distracted as well as undistracted drivers benefited from early warnings of a FCW system. Importantly, distracted drivers specifically benefitted from this FCW system because it was able to offset RT decrements that were found in baseline driving. In sum, the timing of collision warnings is associated with promptness of driver reactions and situational outcome. Given that distracted drivers usually show longer reactions, an adaptive warnings system might act as an imminent collision warning with a rather late warning activation timing in currently attentive drivers and as a cautionary collision warning with early activation timing to allow drivers

sufficient possibilities to initiate an adequate response. Recommended timings are a TTC ranging between 1.5 and 2 s for imminent warnings and 3 to 5 s for cautionary warnings (Huey et al., 1997).

Apart from designing warnings for distracted drivers, a further relevant challenge for the introduction of adaptive ADAS may be the presentation of system behavior according to the driver's mental model, which is considered a relevant design principle for FCW systems (Wilson et al., 1998). It is unclear whether the drivers' understanding of system functioning and thus system acceptance may be impaired in adaptive ADAS, since the form of support changes according to the driver state. Smith et al. (2009) note that the presentation of adaptive and thus changing warnings may lead to irritation in drivers. Similarly, related research on the design of two-stage collision warning systems that adjust the type of warning according to situational criticality and thus also present multiple warnings within one FCW (Campbell et al., 2007) poses concerns regarding driver confusion. Moreover, the comprehensibility of distraction detection itself, i.e., the matching of the predicted and the subjectively experienced driver state may be a relevant aspect for the understanding of adaptive ADAS and driver responding. In the context of drowsiness alerts, which provide feedback about a driver state that is directly accessible by the driver, low system acceptance due to subjectively incorrectly presented warnings are reported (Blanco et al., 2009). As it remains unclear if these theoretical concerns are met for adaptive ADAS, this thesis seeks to identify what happens if drivers experience different forms of warnings according to their distraction by investigating whether they react adequately to them.

### *Reliability of warnings*

Real-time driver monitoring and distraction detection has gained particular research interest in engineers and software developers due to continuous advances in sensor technologies and the fact that they are mandatory for the introduction of distraction adaptive ADAS to the market. The identification of driver distraction can be based on physiological measures such as eye- and head-tracking metrics (Fletcher & Zelinsky, 2007; Kutila, Jokela, Markkula, & Rué, 2007; Liang, Reyes, & Lee, 2007; Mbouna, Kong, & Chun, 2013; Miyaji, Kawanaka, & Oguri, 2009; Pohl et al., 2007; Sigari, Fathy, & Soryani, 2013; Vicente et al., 2015; Weller & Schlag, 2010) or the driver's heart rate (Miyaji et al., 2009). Moreover, driving performance metrics such as speed measures (e.g., Fletcher & Zelinsky, 2007; Zhang, Owechko, & Zhang, 2004), lane position (Kutila et al., 2007; Liang et al., 2007; Pohl et al., 2007; Zhang et al., 2004), or

steering wheel metrics (Liang et al., 2007; Torkkola, Massey, & Wood, 2004) were integrated to identify a distraction state in drivers. It was further proposed that it may be useful to monitor driver inputs to vehicle controls or smart phone sensors (Paruchuri & Kumar, 2015; Torkkola et al., 2004) to infer distraction from the driving task. Given that distraction detection is based on probabilistic estimations of the current driver state, it is prone to detection errors (e.g., Liang et al., 2007; Pohl et al., 2007; Trefflich, 2010). This is reflected by accuracy rates that usually range below 90% for algorithms that try to detect distraction based on multiple features such as eye-tracking, driving parameters, face expression or head pose in laboratory (Liang et al., 2007; Ragab, Craye, Kamel, & Karray, 2014; Zhang et al., 2004) or realistic driving conditions (Kutilla et al., 2007; Li & Busso, 2013). Likewise, in realistic driving conditions, a high number of false negative interventions was found for an adaptive LDW as dynamic lighting conditions impeded distraction detection based on head- and eye-tracking (Pohl et al., 2007). Due to those challenges in detecting and interpreting the driver's current state and thus predicting the driver's need for support, research on adaptive ADAS has used wizard-of-oz techniques to adjust system behavior accordingly (Hajek et al., 2013).

As a result of detection errors, drivers are incorrectly identified as either attentive or distracted, which may lead to incorrect warning output when used in adaptive warning systems (Trefflich, 2010). The erroneous presence or absence of an alarm usually occur in conventional ADAS in complete failures of system behavior and present a risk in adaptive systems only when the adaptation strategy suppresses support. However, as adaptive warning suppression raised both safety and acceptance concerns (Smith et al., 2009), the more relevant effect of distraction detection errors should be incorrectly presented support, i.e., (1) too strong support when the driver monitoring indicates that the driver is distracted when it is not, or (2) too weak support when the driver monitoring falsely indicated that the driver is attentive (for an overview, see Table 2). In general, failures of an adaptive system to present the needed form of support are suggested to induce annoyance and impair safety through their potential adverse effects on system efficiency (Feigh, Dorneich, & Hayes, 2012).

**Table 2.** Overview of detection errors of both environmental sensors used for warning systems in general and in-vehicle driver monitoring sensors used in adaptive warning systems

| Sensors  | Consequences of a faulty detection                  |  |
|--|---|--|
|  | False positive                                      | False negative   |
| Environmental threat detection                         | Warning in situations without threat (false alarms) | No warning in situations with immediate threat (missed alarms) |
| In-vehicle driver monitoring for distraction detection | High support when driver is undistracted            | Low support when driver is distracted                          |

While no research on the effects on incorrectly presented support of adaptive warning systems exists, a body of research on conventional warning functions suggests safety and acceptance impairments due to unreliable assistance. False positive and false negative errors of conventional warning ADAS occur based on simulated failures of sensors detecting environmental and vehicle parameters. Research implies that drivers comply less with systems providing frequent false alarms (Abe et al., 2002; Bliss & Acton, 2003; Cotté et al., 2001; Lees & Lee, 2007; Sorkin, 1988; Yamada & Kuchar, 2006) and that frequent false alarms make drivers decelerate unnecessarily in situations without threat (Maltz & Shinar, 2004). Moreover, false alarms were associated with a reduction in subjectively assessed trust in the system (Abe, et al., 2002; Lees & Lee, 2007). A high number of missed alarms also resulted in decreased system reliance, which was observed for reduced speeding when using collision warning system (Yamada & Kuchar, 2006). These findings suggest that drivers adapt their behavior according to system functioning.

In addition, some studies assessed the direct consequences of misses. Misses of a warning systems resulted in RT delays that were even longer than when no warning system was present (Abe et al., 2002; Mahr, Cao, Theune, Schwartz, & Müller, 2010). In line with those findings on conventional warning functions, the investigation of ACC systems further revealed that drivers had problems to solve a critical situation, when the ACC system failed to react. Such failures resulted in rear-end crashes (Nilsson, 1995; Stanton, Young, & McCaulder, 1997), with more frequent crashes for ACC compared to manual drivers (Nilsson, 1995). Crucially, while the experience of misses was associated with reduced trust ratings, there was an association between the RT delays to missed alarms and trust in the system (Abe et al., 2002). In sum, the results suggest that over-reliance on the support provided by ADAS may be associated with adverse effects such as ignoring misses. Importantly, drivers’ adaptation to

ADAS in a way that may undermine safety, can be regarded as a form of adverse behavioral adaptation (see following chapter “Behavioral adaptation to new technology”).

In sum, due to technical constraints in distraction detection, distraction adaptive ADAS are prone to present support that does not match the driver’s actual needs in the current situation. Given that reliability research shows that both false positive and false negative system functioning can alter driver behavior, erroneous distraction detection can be regarded a major challenge in the development of adaptive ADAS. In accordance with presented findings for conventional ADAS, it is suggested that failures of an adaptive warning system to detect driver distraction may also induce impaired driver behavior. However, the effects of unreliable adaptive ADAS may differ from findings on the effects of unreliable conventional ADAS as adaptive systems still present some form of support in critical situations. To elicit the effects of incorrectly adjusted warnings on safety, failures in a modality-based warning strategy are investigated in Studies 1 and 2.

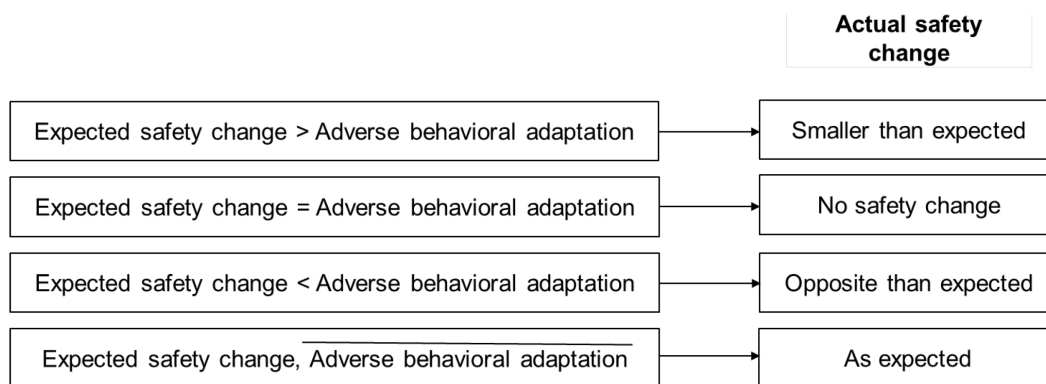
## **Behavioral adaptation to new technology**

In the following section, both definition as well as empirical studies on adverse behavioral adaptation are examined. Moreover, I will provide insight into the different forms of adverse effects that were found to be associated with the use of ADAS. Finally, different theories of behavioral adaptation and their influential factors are described.

### **Definition of behavioral adaptation**

Flexible adaptation to dynamically changing environmental conditions and specific task demands according to individual goals presents a substantial component of human behavior. A specific form of adaptive behavior which has gained major attention in the context of traffic psychology are driver’s behavioral changes that can be observed when drivers get in contact with new technologies such as ADAS. Such adaptations can be defined as “those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change” (Organization for Economic Co-operation and Development [OECD], 1990, p. 23). While the OECD definition does not specifically refer to negative forms of behaviors, research generally uses this term to indicate adverse effects (see e.g., Rudin-Brown & Parker, 2004). Given that adverse behavioral

adaptations may counteract the initially expected positive effects of a safety measure, the final impact of a technology can either be positive, negative or neutral (Evans, 1985; see Figure 2).



*Figure 2.* The different combinations of expected safety changes of a technology and the extent of adverse behavioral adaptation effects result in different impacts on safety. Thus, the actual safety change can be as expected, smaller as expected or even opposite than expected. Moreover, when unexpected adverse effects completely offset the expected safety changes, the introduction of a technology is not associated with any effects on safety; based on Evans (1985).

### Empirical studies on adverse behavioral adaptation to ADAS

Studies have identified adaptation effects in different contexts, such as structural changes of the road environment (e.g., Assum, Bjørnskau, Fosser, & Sagberg, 1999; De Waard, Jessurun, Steyvers, Reggatt, & Brookhuis, 1995; Hakkert & Mahalel, 1978; Lewis-Evans & Charlton, 2006; Mecheri, Rosey, & Lobjois, 2017) or in-vehicle safety systems such as an anti-lock braking system (ABS; Aschenbrenner & Biehl, 1994; Kahane & Dang, 2009; Sagberg, Fosser, & Sætermo, 1997). Moreover and despite their expected ability to improve safety e.g. by increasing perception of critical situations, many examples of unwanted behavioral adaptation effects can be found for ADAS. First, ADAS were found to impair primary task performance. Studies have identified increased driving speeds (ACC; Hoedemaeker & Brookhuis, 1998), riskier gap acceptance (speed adaptation system; Comte, 2000), closer car-following (Comte, 2000; Hoedemaeker & Brookhuis, 1998), more center line crossings (overall ADAS; Adell, Várhelyi, & Fontana, 2011) as well as decreased subjective driving performance (overall ADAS; Adell et al., 2011) in response to the use of ADAS. Second, drivers were found to rely on ADAS in a safety critical way. As described in detail in the previous section (see chapter “reliability of warnings”), system failures are widely associated with impaired driver responses. For example, ACC failures and misses increased drivers’ RTs and thus led to more

critical situations than unassisted driving (e.g., Hoedemaeker & Brookhuis, 1998; Hogema & Janssen, 1996; Rudin-Brown & Parker, 2004; Stanton, Young, Walker, Turner, & Randle, 2001; Young & Stanton, 2007). Third, providing drivers with support may motivate them to perform non-driving related activities. Increased engagement in secondary tasks was found as a consequence of decreased workload and freed resources when using ACC (Carsten, Lai, Barnard, Jamson, & Merat, 2012; Malta et al., 2012; Rudin-Brown & Parker, 2004; Stanton et al., 1997; for a review, see De Winter, Happee, Martens, & Stanton, 2014), lane keeping assistance (Carsten et al., 2012; Stanton et al., 2001) or warning systems (Naujoks & Totzke, 2014).

Taken together, research provides evidence for a multitude of different forms of adverse behavioral adaptation effects that could manifest themselves after the introduction ADAS ranging from impaired responses in failure situations, riskier driving and attention allocation towards non-driving related stimuli. Since the heterogeneity of findings implies that the exact form of behavioral adaptation strongly depends on the specific system and thus the specific form of driver support, behavioral adaptation should be examined before the introduction of new ADAS. Since adaptive ADAS present a new technology, potential adverse effects of such systems have not yet been empirically investigated. However, as such ADAS are expected to become more common in future vehicles, the possibility of adverse behavioral adaptation to such systems certainly needs to be evaluated to allow for a prediction of the systems' final impact on safety.

### **Theories of behavioral adaptation**

Different theoretical models have attempted to account for the explanation of behavioral adaptation effects that occur after the introduction of in-vehicle technologies or other changes in the driving environment. Early models that were developed from the 1970s utilized the concept of risk and suggested that drivers regulate their behavior according to a certain level of risk via feedback mechanisms. In their threshold model, Näätänen and Summala (1974) indicate that risk is generally avoided by drivers. According to their "zero risk theory" drivers aim to avoid fearful experiences and thus adapt their behavior when a subjective level of zero collision risk is exceeded. In contrast, Wilde's (1982) well-known risk homeostasis theory claims that drivers assess a certain risk level. It assumes that a driver tries to maintain an individual target level of risk. While driving, the driver experiences a subjective risk based on the perceived crash risk. Again, as soon as the experienced risk deviates from the tolerated target risk, the

driver initiates corrective actions by either decreased or increased risk taking which is expected to result in constant crash rates. Later, Fuller (2000, 2005) proposed a model in which the discrepancy between the task demands of the current situations and driver's capabilities accounts for behavioral changes such as speed adjustments as drivers aim to maintain a certain difficulty level. Importantly, however, while those well-known models are able to describe common behavioral adaptation effects, they have two important shortcomings for system designers. First, they do not specifically account for adaptation effects in ADAS and crucially, as noted by Rothengatter (2002), they cannot be used as a basis for developing countermeasures.

More recent models on adaptation in ADAS (Rudin-Brown, 2010; Rudin-Brown & Noy, 2002; Rudin-Brown & Parker, 2004; Weller & Schlag, 2004), risk factor assumptions (Hedlund, 2000) and even specific check-lists for predicting behavioral adaptations to safety measures (Elvik, 2004) provide the basis for experimentally testable hypotheses regarding behavioral adaptation effects in ADAS as well as overall contributing factors. Among all factors reported to be relevant for the development of adverse behavioral effects in drivers, however, only few can be directly influenced by system design. First, the general effect of a measure was considered an important factor influencing the probability of adverse behaviors (Bjørnskau, 1994, as cited in Amundsen & Bjørnskau, 2003; Elvik, 2004). The objective effect the measure has on injury severity and material damage as well as the extent to which the measure improves safety relevant parameters such as friction or sight should be predictive of the occurrence of adverse behavior (Elvik, 2004). Moreover, the subjective safety benefit associated with the measure should contribute to the development of behavioral adaptations (Elvik, 2004; OECD, 1990). According to Hedlund (2000), drivers may compensate only if the measure increases perceived safety. An example for increases in adverse effects according to the system's effect on safety is that drivers engage more intensively in a non-driving related secondary task when they drive with full relative to partial automation (Carsten et al., 2012; Llaneras, Salinger, & Green, 2013; but see also Naujoks, Purucker, & Neukum, 2016 for different results regarding a comparison between partial automation and assisted driving). Moreover, in surveys by Rudin-Brown, Jenkins, Whitehead, and Burns (2009) and Vadeby, Wiklund, and Forward (2011) drivers reported that the increased perceived driving safety due to electronic stability control (ESC) made them take more risks. Second, the awareness of system behavior is expected to influence the likelihood of behavioral adaptation effects. According to Grembek (2010), the greater the perceptibility of the system, the greater the risk that users will adapt their behaviors to it. Moreover, it is claimed to be important not only whether the measure itself can be detected, but also the extent to which changes associated with the measure are obvious to the driver



(Elvik, 2004). Similarly, the feedback of a measure provided to the user is widely proposed to be an indicator for the occurrence of adverse behavioral adaptation (Hedlund, 2000; OECD, 1990; Rudin-Brown, 2010; Rudin-Brown, Jonah, & Boase, 2013; Rudin-Brown & Noy, 2002; Weller & Schlag, 2004). Table 3 provides an overview on factors similar to “awareness of system behavior” that were suggested to influence adverse behavioral adaptation in different contexts of the driver, the vehicle and the road environment. A first study that tried to find out whether system awareness is associated with adverse effects compared survey data that measured the extent to which systems are obvious to the user with published driving data (Grembek, 2010). Results suggest a positive association between adverse behavioral adaptation effects and system awareness.

**Table 3.** List of proposed factors comparable to “awareness of a system” influencing behavioral adaptation to protection systems, ADAS and safety measures in general (based on Grembek, 2010)

| <b>Reference</b>                   | <b>Proposed factor</b>              | <b>Context</b>    |
|------------------------------------|-------------------------------------|-------------------|
| Elvik (2004)                       | <i>Noticeability</i>                | Safety measure    |
| Grembek (2010)                     | <i>Perceptibility</i>               | Protection system |
| Hedlund (2000)                     | <i>Visibility</i>                   | Safety measure    |
| Hedlund (2000)                     | <i>Direct feedback</i>              | Safety measure    |
| Kulmala (2010)                     | <i>Detectability</i>                | Safety measure    |
| OECD (1990)                        | <i>Immediacy of feedback</i>        | Safety measure    |
| OECD (1990)                        | <i>Interaction with the measure</i> | Safety measure    |
| Rudin-Brown (2010)                 | <i>Direct and inferred feedback</i> | ADAS              |
| Rudin-Brown, Jonah, & Boase (2013) |                                     |                   |
| Rudin-Brown & Noy (2002)           |                                     |                   |
| Rudin-Brown & Parker (2004)        |                                     |                   |
| Rudin-Brown et al. (2013)          | <i>Quality of feedback</i>          | ADAS              |
| Weller & Schlag (2004)             | <i>System feedback</i>              | ADAS              |

In sum, it was shown that theoretical assumptions have identified contributing factors for adverse behavioral adaptation. However, empirical research has not yet specifically investigated whether risk factors are indeed associated with increases in the probability of adverse effects. Therefore, it remains unclear to what extent risk factors play a role in the development of adverse behaviors and how they may be considered in the design and development of adaptive, warning ADAS.

## Research questions

The following studies aim to investigate the overall effects of distraction adaptive warning signals by addressing both the expected positive effects on safety due to tailored support as well as potential adverse behavioral adaptation. As a starting point, I want to examine the potential of adverse behavioral adaptation in a generic adaptive warning paradigm. Subsequent investigations aim to gain insight into the expression of behavioral adaptation as a result of the usage of more realistic adaptive FCWs. As a system could influence driver behavior in different forms, I want to gain insight into adverse behavioral effects on both potential primary task performance decrements and the risk of secondary task engagement while driving in response to adaptive FCWs. Also, underlying factors that may explain the occurrence of such adverse behavioral effects are addressed. In sum, the driving simulator and test-track studies answer the following research questions:

- Do the investigated adaptation strategies have the potential to compensate for distraction deficits?
- Do the investigated adaptation strategies induce adverse behavioral adaptation in drivers?
- Which factors account for adverse behavioral adaptation to adaptive ADAS?

Beyond these main research questions, some subordinate aspects should be addressed in this thesis. A first aspect concerns the acceptance of the investigated adaptive warnings. A further subordinate goal is to provide methodological implications for future investigations of distraction adaptive ADAS. Moreover, my findings should lead to an understanding of relevant implications that could be utilized by designers and researchers for the development of more effective adaptive ADAS.

An overview of all studies is presented in Table 4. *Study 1* investigated driver reactions to a generic adaptive warning strategy that adjusted warning parameters according to occasionally presented in-vehicle conversations. Driver distraction was inferred from the engagement in conversation based on a wizard-of-oz paradigm. While driving a vehicle on a test track participants had to manually react to two types of signals, auditory signals that were presented in situations without distraction and vibrotactile-auditory signals that were presented in distraction situations. This compensating warning strategy was compared to a *non-compensating warning strategy*, in which the match between distraction situation and signal

type was reversed. Crucially, to allow for the investigation of driver reactions to failures of adaptive warning signals, signals were presented in accordance with the underlying warning strategy in only 80% of trials. This approach allowed to find out if drivers show adverse behavioral adaptation effects in situations in which the warning strategy fails to present the expected support. By further manipulating the drivers' awareness of the functioning of the underlying warning strategy, we investigated the significance of this risk factor for the development of adverse behavioral adaptation effects. This study aimed to provide insight into the potential of a modality-based adaptation strategy to compensate for deficits associated with driver distraction, while at the same time identifying the impact of system awareness on potential adverse behavioral adaptation effects to system failures.

**Table 4.** Overview of the conducted studies with focus on research content and method. BA = adverse behavioral adaptation

|                | Research content        |                           |                             | Research method                |   |   |   |
|----------------|-------------------------|---------------------------|-----------------------------|--------------------------------|---|---|---|
|                | Adaptation strategy     | Investigated form of BA   | Investigated factor for BA  | Tool                           | External validity                             | Measure of BA   | Realization of adaptation                 |
| <b>Study 1</b> | HMI-based: Modality     | Reaction to system errors | Awareness                   | Vehicle on test track          | Low (generic adaptive warning strategy)       | Explicitly through frequently experienced system behavior | Wizard-of-oz                              |
| <b>Study 2</b> | HMI-based: Modality     | Reaction to system errors | Safety effect               | Motion based driving simulator | Medium (adaptive ADAS with frequent warnings) | Explicitly through frequently experienced system behavior | Wizard-of-oz                              |
| <b>Study 3</b> | Algorithm-based: Timing | Primary / secondary task  | Awareness / system feedback | Motion based driving simulator | High (adaptive ADAS with rare warnings)       | Implicitly through anticipated system behavior            | Real-time distraction detection algorithm |

Following the first attempt to identify driver reactions to failures of a generic adaptive warning strategy, *Study 2* aimed to extend this approach to a more realistic context in which drivers react to hazardous situations while being supported by adaptive FCW. To this aim, I implemented two adaptive FCW systems in a driving simulator setting that adjusted warning parameters according to the presentation of a non-driving related secondary task. A modality-based adaptation strategy changed the type of warning triggered in critical brake events from visual support to visuo-haptic support when the driver was engaging in a non-driving related secondary task. Contrasting driving performance with a non-adaptive FCW to driving performance with an 80% reliable adaptive FCW allowed for the investigation of two crucial aspects of adaptive support: compensation and expectancy. While the previous study addressed the potential of visuo-haptic support to compensate for performance deficits in distracted drivers, the latter addressed whether and to what extent impaired performance in response to failures in the adaptive warning strategy stems from the violation of the driver's expectation to receive adaptive support, which thus represents a form of adverse behavioral adaptation. By implementing two variants of adaptive FCWs that differed in the intensity of adaptive support, I further aimed to investigate safety effects of the system as a potential risk factor for adverse behavioral adaptation in drivers.

Finally, *Study 3* focused on the potential of an adaptive FCW to induce changes in primary and secondary task performance in drivers. Therefore, a real-time distraction detection-algorithm was implemented in a driving simulator scenario. In contrast to the previous studies, in which explicit reactions to frequently presented warnings were assessed, the final study examined driving performance resulting from anticipated system behavior. To this end, I examined driver behavior when drivers drove multiple road sections with both an adaptive and a non-adaptive FCW without presenting critical brake events. Following the initial attempt to identify the impact of system awareness as risk factor for adverse behavioral adaptation, in *Study 3* system feedback was manipulated by making the actual behavior of the underlying adaptation strategy visible or not. Based on this manipulation, the potential of HMI design to alter driver behavior could be derived as additional question. By presenting an unexpected critical brake event when distracted drivers used both an adaptive and non-adaptive FCW at the end of the experimental session, the potential of another warning strategy, which adjusts warning timings according to driver distraction to increase driving performance was assessed.

## **Study 1: Adaptive warning signals adjusted to driver-passenger conversation: Impact of system awareness on behavioral adaptation**

By Katharina Reinmueller, Linda Koehler, and Marco Steinhauser

### **Abstract**

The study investigated behavioral adaptation caused by warning signals that adaptively support drivers engaged in a passenger conversation. Novel advanced driver assistance systems (ADAS) could monitor the driver state to provide warnings adjusted to the driver's current need for support. While first research indicates positive effects of dynamically adjusting ADAS, the overall safety potential of such adaptive systems remains unclear as little is known about adverse behavioral effects. Occasional inappropriate support due to an incorrect prediction of the current driver state might lead to critical situations when drivers are aware of the adaptive nature of the system and thus rely on the expected system behavior. To better understand behavioral adaptation to dynamically adjusting warnings, 46 participants driving on a test track reacted to two types of warnings (auditory, vibrotactile-auditory) while engaging in driver-passenger conversation or not. In a compensating warning strategy, vibrotactile-auditory warnings were displayed during conversations and auditory warnings in situations without conversation. This strategy was compared to a non-compensating warning strategy in which these assignments were reversed. The impact of behavioral adaptation was measured by considering reactions to simulated failures of these strategies. The role of system awareness for behavioral adaptation was investigated by manipulating awareness of these warning strategies across groups. We found that vibrotactile-auditory warnings reduced the detrimental effects of conversation on reaction times. Crucially, adverse behavioral adaptation was observed whenever an expected vibrotactile-auditory warning was replaced by an auditory warning, but this effect was restricted to drivers in the awareness group. The results show that adaptive warning signals optimize the effectiveness of warnings during driver-passenger conversation, but adverse behavioral adaptation develops when drivers are aware of the underlying warning strategy. This implies that future adaptive systems are less likely to be associated with behavioral adaptation if the adaptive nature of the system remains unnoticeable to the driver. Our findings could be used for developing and optimizing user-centered ADAS.

**Keywords:** Adaptive warnings; Driver distraction; Behavioral adaptation; System awareness

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## **Study 2: Adaptive forward collision warnings: The impact of imperfect technology on behavioral adaptation, warning effectiveness and acceptance**

By Katharina Reinmueller and Marco Steinhauser

### **Abstract**

Adaptive ADAS that adjust warnings according to the driver's current need for support offer a great potential to increase safety. However, it is crucial to understand how drivers deal with dynamically adapting technologies particularly in situations in which driver state monitoring fails and the system shows unexpected behavior. To better understand the consequences of unreliable adaptive ADAS on safety and to assess how failures of an adaptive FCW influence driving behavior, we conducted a driving simulator study with  $N = 48$  participants. Participants experienced critical brake events in situations with and without a distracting secondary task. An adaptive FCW provided visual warnings to undistracted drivers but highly supportive visuo-haptic warnings (brake jerks or vibration) to distracted drivers. In 20% of brake events, however, the system unexpectedly provided incorrectly adapted warnings in which the combination of warning type and distraction was reversed. This adaptive FCW was compared to a non-adaptive standard FCW that provided visual warnings only. We found that incorrect warnings impaired driver reactions and safety in distracted drivers, and these adverse behavioral effects had two sources: (1) Violations of the drivers' expectancies about the warning, and hence, behavioral adaptation. (2) The absence of the compensatory effect of the highly supportive warning in case of distraction. In contrast, correctly adapted warnings reduced decrements in brake reaction times and fully offset safety deficits associated with driver distraction. Crucially, however, an effectiveness evaluation of the adaptive system's potential to support drivers when correct warnings were elicited failed to demonstrate a benefit of the adaptive FCW over the non-adaptive FCW. Our results thus emphasize that a high reliability is crucial for adaptive ADAS to improve safety and to prevent adverse effects due to behavioral adaptation.

**Keywords:** Rear-end collision; Forward collision warning; Driver distraction; Behavioral adaptation; Driving simulator

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## **Study 3: Adverse behavioral adaptation to adaptive forward collision warning systems: An investigation of primary and secondary task performance**

By Katharina Reinmueller, Andrea Kiesel, and Marco Steinhauser

### **Abstract**

Advanced driver assistance systems can effectively support drivers but can also induce unwanted changes in behavior. The present study investigates this adverse behavioral adaptation in adaptive Forward Collision Warning (FCW) systems. Other than conventional FCW systems, which provide warnings based on static Time-To-Collision (TTC) thresholds, adaptive FCW systems further consider the driver's need for support by adjusting warning thresholds according to distraction. A neglected question is how drivers adapt their behavior when they use adaptive FCW systems under realistic conditions, i.e., when warnings occur infrequently, but system functionality is anticipated. Forty-eight participants drove with two different FCW systems (adaptive vs. non-adaptive) while working on a secondary in-vehicle task in a driving simulator. During the main part of the experiment, no brake events occurred and hence FCW functioning was largely anticipated. Additionally, visual system feedback about the driver's distraction state was manipulated across groups. Participants had significantly shorter minimal time-headways and TTCs when driving with the adaptive relative to the non-adaptive system. Participants with system feedback about distraction state spent generally more time with engaging in the secondary task. These results indicate behavioral adaptation which, however, is restricted to the task that is specifically supported by the system, namely longitudinal control.

**Keywords:** Driver behavior; Collision warning; Behavioral adaptation; Driver distraction; Driver monitoring

Reinmueller, K., Kiesel, A. & Steinhauser, M. (2019). Behavioral adaptation effects in adaptive forward collision warning systems: an investigation of primary and secondary task performance. Manuscript submitted for publication.



## Discussion

The main goal of the three studies presented in this thesis was to systematically examine how drivers change their behavior according to the use of distraction adaptive ADAS. Thus, this thesis provides diverse contributions to research on adaptive ADAS. A first contribution of this thesis is to provide systematic empirical evidence for the influence of adaptive warnings on driving performance and safety. As the adjustment of ADAS has been predicted to be able to increase safety and acceptance, this thesis provides insight into how successful adaptation strategies may be in offsetting distraction induced deficits. To provide a holistic evaluation of adaptive warning strategies, user acceptance was also investigated. A second contribution is to provide insight into adverse behavioral adaptation that may arise with the introduction of adaptive warning strategies. The thesis thus investigates different adverse behavioral tendencies that may counteract the expected positive effects associated with system usage. Knowledge about the exact forms of adverse behavioral adaptation allows for more accurate predictions on newly developed system's effects on real-world safety. A third contribution is to evaluate the impact of potential factors that may account for the development of adverse behavioral effects in response to adaptive ADAS. Therefore, it was tested whether system awareness or safety are associated with the development of adverse behavioral adaptation effects. As the thesis focused on factors that could be influenced in the system development process, practical implications that may help to develop more successful adaptive ADAS are presented.

This concluding chapter summarizes the main results obtained from the empirical studies and relates them to the central research questions which were previously identified (see chapter "Research questions"). Moreover, both the acceptance of adaptive warning functions as well as practical implications derived from the empirical findings are discussed with regard to the development of future adaptive warning functions. Finally, also methodological considerations and limitations are outlined in the following.

### **Do the investigated adaptation strategies have the potential to compensate for distraction deficits?**

Evidence suggests that driver distraction is related to various forms of driving deficits and increased crash risk. It was often demonstrated that distraction leads to deficits in perceiving and adequately reacting to current developments of the driving situation (e.g., Alm & Nilsson, 1995; Atchley & Dressel, 2004; Desmet & Diependaele, 2019; Hancock et al., 2003; Harbluk et al., 2007; McCarley et al., 2004; McKnight & McKnight, 1993; Salvucci &

Beltowska, 2008; Strayer & Drews, 2007; Strayer et al., 2003; Strayer & Johnston, 2001). Considering the effects of distraction, this thesis investigated the overall potential of adaptive warnings to mitigate the deficits associated with driver distraction. Given that impairments in responding adequately to a relevant stimulus present a common deficit that can be found both during visual (Lee et al., 2002; Olsson & Burns, 2000) or during cognitive distraction (Alm & Nilsson, 1995; Gugerty et al., 2004), all conducted studies addressed RT as a main dependent variable for quantifying the distraction mitigation effect. I investigated different types of adaptation strategies, namely timing and modality-based adaptation strategies by comparing their influence to those of conventional non-adaptive warnings. Both strategies were successful in the sense that the adaptive warnings facilitated distracted drivers' responses relatively to non-adaptive warnings. However, irrespective of the underlying warning strategy, adaptive warnings had no positive impact on the criticality of lead-vehicle brake events.

As a starting point, my findings confirmed how detrimental the effects of cognitive and visual-manual distraction are, which in turn demonstrates the potential of adaptive warnings. An investigation of driving behavior associated with driver-passenger conversations in Study 1 identified various deficits, which were expressed in terms of increased proportions of sign-violations due to perception and interpretation errors. The results thus confirm previous findings of impairments in perceiving and reacting adequately to task-relevant stimuli due to conversation (e.g., Alm & Nilsson, 1995; Consiglio et al., 2003; Gugerty et al., 2004; Kass et al., 2007; Ma & Kaber, 2005) and therefore allow justifying the development of distraction adaptive ADAS that aim to adjust according to different types of distraction that commonly occur during driving.

Based on previous research showing that earlier warning timings to collision situations were associated with faster driver reactions (Abe & Richardson, 2004; Hirst & Graham, 1997; Lee et al., 2002), Study 3 evaluated a timing-based adaptation strategy which adjusted the TTC-thresholds according to detected visual-manual distraction. The strategy proved successfully that presenting earlier warnings to distracted drivers had led to faster and less variable RTs than later warnings of the non-adaptive FCW. Study 1 and Study 2 have focused on HMI-based strategies that added a modality when the driver was identified as distracted in a critical collision situation. Extending the findings of previous studies investigating different forms of support for distraction mitigation (Blaschke et al., 2009; Mohebbi et al., 2009) and adaptive collision warnings (Smith et al., 2009), Study 1 was able to reveal the positive effect of an added warning modality on RT in distracted drivers who are supported with dynamically

changing warning parameters as tactile-auditory warnings prompted faster driver reactions compared than a auditory warning in conversation situations.

Similarly to this compensation effect, Study 2 showed that the adaptive FCW which presented visual-auditory warnings in distraction situation, could better offset RT deficits associated with distraction than the non-adaptive FCW. Different explanations can account for this compensation effect of the modality-based adaptation strategy. Faster responses through the presentation of redundant signals are robustly found in cognitive psychology research for different targets (see e.g., Gondan, Niederhaus, Rösler, & Röder, 2005; Grice, Canham, & Boroughs, 1984; Grice & Reed, 1992; Miller, 1982, 1986; Mordkoff & Yantis, 1991; Raab, 1962) and can be explained by different models of redundancy gain (e.g., Miller, 1982; Raab, 1962). The finding of enhanced responses to bimodal warnings during distraction could also be explained by multiple resources theory (Wickens, 1980, 1984, 2002, 2008), which is based on the assumption of independent sensory modalities. By presenting a tactile warning modality together with (1) the default auditory signal when drivers engaged in conversation in Study 1, and (2) the default visual signal when drivers solved a rapid serial visual presentation (RSVP) task in Study 2, drivers received warnings in an additional modality that produced a smaller degree of resource overlap than the default signals as they consumed different attentional resources than the distracting task. In general, results are in line with previous studies identifying a positive effect of multimodal over unimodal warnings in terms of briefer RTs (Biondi et al., 2017; Maier et al., 2014).

The present results suggest that adaptation strategies for FCWs may facilitate distracted driver's response timing by providing early and multimodal warning signals. Yet, future research on adaptive warnings could build on these results and evaluate other adaptation approaches such as the use of spatial properties like location and direction. For example, adjusting the presentation location of warnings to the current focus of attention should immediately draw the driver's attention. Based on this adaptation strategy, gaze guidance could then be used to direct a visually distracted driver's attention to the location of the hazard. Indeed, it has been shown that automatic gaze guidance can facilitate both driver's attention allocation to hazards and BRTs (Lorenz, 2014). Moreover, using directional warnings, which either provide endogenous or exogenous cues that are predictive of the hazard location may be a useful adaptation strategy to specifically provide additional support to distracted drivers. While spatial cuing paradigms (e.g., Posner, 1980; Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980) demonstrate performance benefits to targets presented at a cued

relative to an uncued location, applied studies testing the performance of drivers and pilots have also demonstrated the potential of spatial haptic (Ho, Tan, & Spence, 2005), visual, (Weller et al., 2014), visual-auditory (Weller et al., 2014) or auditory warnings (Begault, 1993) to improve the perception of hazards compared to non-spatial warnings.

While results show a compensation effect of high-supportive warnings of an adaptive FCW on response timing in distracted driving, criticality measures draw a more complex picture of the effects of adaptive FCW on safety. Study 2 demonstrated a compensation effect of high-supportive warnings. Drivers showed higher minimal TTCs in brake events when high-supportive bimodal compared to unimodal warnings were presented. In Study 3, criticalities regarding the outcome of brake events were not generally decreased when distracted drivers' were supported by the adaptive relative to the non-adaptive FCW. In line with findings on the association between RT and deceleration in simulated driving (Naujoks, Kiesel, & Neukum, 2016), test track driving (Hancock et al., 2003) as well as naturalistic near-crash driving situations (Wood & Zhang, 2017), results imply that after the initial brake reaction, drivers generally adapted their brake behavior and therefore may have compensated later brake onsets by stronger decelerations. Furthermore, driver braking behavior analyses by Markkula, Engström, Lodin, Bårgman, and Victor (2016) found that both BRTs and deceleration behavior depend on situational urgency, which is usually high for distracted drivers who perceive the danger on the road late in the situation.

Study 2 also investigated the overall safety effect of an adaptive FCW relative to a non-adaptive FCW. While this study provided both reliable and unreliable adaptive warnings, only reliable system behavior was considered and analyzed. Still, no benefits for the adaptive FCW were found regarding criticality measures but also response timing. However, this lack of safety benefit resulted from undistracted drivers' behaviors. Undistracted drivers showed the tendency to react to adaptive warnings in a more unsafe manner than to non-adaptive warnings. Importantly, this effect may stem from the systems' differences in reliability.

In sum, I could show that timing-based and modality-based adaptation strategies provide a potential benefit in the initial reaction to a presented warnings as adaptive warnings speed up driver reactions and thus are better able to compensate for deficits associated with distraction than non-adaptive warnings. Thus, findings suggest that providing distracted drivers with additional support may promote faster attention allocation to the relevant stimulus and enhance time to prepare and initiate a response. Thus, both algorithm-based and HMI-based adaptation strategies (see chapter "Definition and functioning of adaptive ADAS", Table 1) are able to

offset some of the decrements associated with distracted driving. The findings extend previous studies on the possibility of earlier and multimodal warnings to promote faster reactions, which have considered isolated effects of warnings according to distracted driving effects without investigating them in the context of dynamically changing, adaptive warnings (e.g., Biondi et al., 2017; Bueno et al., 2014; Lee et al., 2002; Lee & Spence, 2008; Mohebbi et al., 2009). Crucially, despite of the compensation effect of the adaptive warnings found in distracted drivers' RTs, my findings also suggest that adaptive FCWs do not automatically enhance overall safety, especially when they are experienced being not 100% reliable.

### **Do the investigated adaptation strategies induce adverse behavioral adaptation in drivers?**

The introduction of new ADAS can result in adverse behavioral adaptation in terms of unexpected and unfavorable driver behaviors. The importance of considering such adverse behavioral effects has been demonstrated in many studies that have reported behaviors such as deficits in primary driving performance (e.g., Adell et al., 2011; Comte, 2000; Hoedemaeker & Brookhuis, 1996), increased attention towards non-driving related tasks (e.g., Hogema & Janssen, 1996; Rudin-Brown & Parker, 2004; Stanton et al., 2001) and problems in taking over control in error situations following the usage of ADAS as compared to unsupported driving (e.g., Carsten et al., 2012; Malta et al., 2012; Naujoks & Totzke, 2014; Rudin-Brown & Parker, 2004; Stanton et al., 2001). Even though concerns about adverse behavioral effects have been raised in the context of adaptive ADAS and distraction mitigation systems in general, no indicators of adverse effects in adaptive ADAS have been reported so far. Therefore, the thesis investigated whether adaptive warnings have the ability to induce adverse behavioral adaptation effects in drivers. While Study 1 assessed driver reactions to generic and thus unspecific adaptive warnings, Studies 2 and 3 specifically aimed at identifying the exact types of adverse effects associated with the introduction of adaptive FCWs. My results suggest that drivers adapt adversely to adaptive warning strategies in different ways: Results show clear performance deficits to sudden failures of adaptive warning strategies, possibly due to an expectancy effect. Moreover, the use of an adaptive FCW was found to be associated with riskier car-following behavior in terms of shorter time headways (THWs).

Studies 1 and 2 of this thesis investigated driver reactions in situations in which adaptive strategies occasionally failed to adjust warning parameters according to distraction and thus unexpectedly provided less strong support. Such erroneous presentations of adaptive warnings

could stem from incorrect detections of underlying distraction detection algorithms. Given that distraction detection, just like other technical systems, will not be 100% reliable, it is important to minimize the risk resulting from failures to present correctly adjusted system behavior.

Study 1 investigated a generic adaptive warnings strategy, in which drivers had to react to distraction adjusted unimodal and bimodal warnings by pressing a button during driving. I found that the unexpected presentation of unimodal instead of bimodal support to currently distracted drivers led to clear RT impairments in drivers who were aware of the system's adaptive functionality. By introducing a further strategy, that specifically supported currently undistracted drivers and thus functioned contrariwise to the adaptive warning strategy as a baseline, to the same drivers, I showed that these detected RT impairments in erroneous situations were more pronounced than what had been expected based on distraction and warnings modality alone. While Study 1 investigated adverse effects associated with failures of a generic warning strategy, Study 2 extended these findings as it tested such effects in concrete adaptive FCW systems where all subjects were provided with detailed information about the functioning of the adaptive system via operation manual and thus provided a more realistic setting. I could show that expectancy effects were not restricted to RTs: in addition to slower reactions, currently distracted drivers also experienced higher situational criticality and a higher frequency of near-crash situations when the visual warning had been triggered unexpectedly by the adaptive FCW than when it had been triggered as expected by the non-adaptive FCW. Similarly to Study 1, the results reflect an expectancy effect indicating that distracted drivers rely on the expected highly supportive warnings of an adaptive warning strategy, and thus show the negative tendency to allocate less resources to the processing of the redundant visual signal. Moreover, in Study 2 the resulting adverse reactions to failures of the adaptive warning system in distracted drivers can be attributed to the absence of the compensation of distraction deficits using supportive, vibrotactile warnings in distracted drivers. Given that the reliability of the presented system influences how drivers interact with it (e.g., Bliss & Acton, 2003; Chancey, Bliss, Yamani, & Handley, 2017; Dixon & Wickens, 2006), investigating the effect of differentially reliable adaptive warning systems while taking the effect of false positive and false negative warning presentation into account appears to be an important area for future research.

Further adverse behavioral adaptation effects to adaptive FCWs are confirmed in Study 3. There, both primary task performance as well as secondary task engagement while driving with an adaptive FCW were analyzed and compared to the interaction with a non-adaptive FCW

to provide evidence for adverse behavioral adaptation effects to adaptive systems. Importantly, Study 3 differed from the other studies as no critical brake event was triggered during the experimental drive. However, drivers were introduced to the idea and functioning of a distraction adaptive FCW at the beginning of the experimental session. A key goal behind this experimental design was to provide a more realistic setting as forward collision scenarios occur infrequently and thus are unexpected in real-world driving. It was shown that driving with a distraction adaptive FCW, that adjusted warning timing according to a detected distraction state in drivers, was associated with shorter headways as well as decreased TTC values and thus riskier behavior in a car-following scenario than baseline driving with a non-adaptive FCW. This form of adverse behavioral adaptation reflects that drivers may have possibly compensated the anticipated safety benefit of earlier warnings in terms of an enhanced time to prepare and execute a response to an emerging collision. Similar patterns of shorter headways and thus adverse changes on the operational driving level were also observed for the usage of ABS (Sagberg et al., 1997) and ACC systems (Hoedemaeker & Brookhuis, 1998). Interestingly, even though drivers have almost never actually experienced a collision event during the drive and thus the specific functioning of the adaptive FCW was mostly not directly accessible, drivers still behaved differently when the adaptive relative to the non-adaptive FCW was activated. This observation provides evidence that knowledge of system behavior leads to anticipation even without the explicit experience of system performance and associated benefits in safety. Our findings also seem to resemble findings in the context of mental models of ADAS, which show that drivers behave according to initial knowledge about system functioning (Beggiato & Krems, 2013).

In short, the results of all studies provide evidence that drivers form expectations about the form of support they receive when they are distracted and do rely on it. Accordingly, adaptive strategies and systems are associated with adverse behavioral adaptation effects whenever those expectations are violated. The presented results on impaired reactions to failures of an adaptive warning strategy extend previous knowledge on driver reactions to erroneous systems, which have so far been investigated in conventional, non-adaptive ADAS (Abe et al., 2002; Hogema & Janssen, 1996; Larsson, Kircher, & Hultgren, 2014; Mahr et al., 2010; Nilsson, 1995; Yamada & Kuchar, 2006). However, more evidence on the effects of naturalistic driving and long-term usage is needed to confirm the external validity of the present findings.

### **Which factors account for adverse behavioral adaptation to adaptive ADAS?**

Current knowledge about the prevention of adverse behavioral adaptation is mainly derived from theoretical models and assumptions of risk factors. It has further been proposed that there is a risk of behavioral adaptation by means of increased distractions to occur in systems that specifically aim at mitigating distraction in drivers (Donmez et al., 2003; Young & Regan, 2013). While estimating the importance of known risk factors for behavioral adaptation in adaptive ADAS, my studies focused on potential risk factors that can be manipulated by system design and thus influenced by manufacturers for future system developments. That way, I provide implications on how such factors for unwanted behavioral adaptation can be addressed in the development of adaptive ADAS. Whereas Studies 1 and 3 addressed the awareness and feedback of system behavior, in Study 2, the safety effect of an adaptive warning strategy was taken into consideration. Awareness was confirmed as a potential risk factor for the development of adverse behavioral adaptation effects. However, I was not able to provide direct empirical evidence for an increased risk of adverse behavioral effects to adaptive functions due to enhanced safety.

Adverse behavioral adaptation effects in terms of impaired RT to failures of the adaptation strategy - in terms of unexpectedly presented unimodal instead of bimodal support - were restricted to drivers who were informed about the functioning of the warning strategy and thus were aware of adaptivity in Study 1. In the absence of consciously accessible knowledge of the association between driver distraction and warning signal presentation, participants were not able to detect the association. The absence of adverse behavioral adaptation in drivers who were not aware of the system's functionality shows that they were not able to implicitly learn the association between signal and driver distraction, to predict the upcoming signal and thus to adapt their response accordingly. Evidence from cognitive psychology suggests that indeed implicit learning may fail, e.g., when participants do not attend to the relevant stimuli (e.g., Hoffmann & Sebald, 2005; Jiang & Chun, 2001). By showing that explicit awareness could make drivers rely on the expected support and thus results in slowed responses to failures, results clearly suggest that the awareness of system functioning is an important prerequisite for the development of adverse behavioral adaptation. This finding is consistent with theoretical assumptions about the adverse influence of the feedback of the measure (Hedlund, 2000; OECD, 1990; Rudin-Brown & Parker, 2004), its perceptibility (Grembek, 2010), noticeability (Elvik, 2004), and visibility (Hedlund, 2000; for a review, see Grembek, 2010). Moreover, Study 3 found that when drivers had explicit initial knowledge about an adaptive FCW, the



anticipated use of an adaptive FCW induced riskier driving by means of shorter headways and decreased TTC values during car-following than the anticipated use of a non-adaptive FCW. Thus, this thesis provides findings that confirm the proposed effect of indirect information on the development of adverse behavioral adaptation effect (Rudin-Brown, 2010; Rudin-Brown & Noy, 2002; Rudin-Brown & Parker, 2004; Weller & Schlag, 2004). Moreover, Study 3 found that when explicit knowledge is has already been given, a further manipulation of system feedback, by making distraction detection and thus system functionality more transparent to some drivers, directly influences secondary task performance. Thus, direct access to underlying algorithms of distraction detection could result in adverse behavioral adaptation in terms of increased attention allocation towards non-driving related stimuli. This increased secondary task engagement by means of an increased proportion of off-road glances and solved tasks due to real-time feedback of the underlying algorithm may be explained by an enhanced motivation to make use of the additional safety margin expected from the system during distraction. Furthermore, system feedback could have increased the perceived support associated with the system and thus induced a higher subjective safety margin associated with the system. Results extend previous knowledge showing that drivers adapt secondary task performance in accordance to the driving demands (e.g., Carsten et al., 2012; Liang, Horrey, & Hoffman, 2014; Llaneras et al., 2013; Metz & Krüger, 2011; Metz, Schömig, & Krüger, 2011; Tivesten & Dozza, 2015; Wandtner, Schumacher, & Schmidt, 2016).

As the safety effect of a measure is assumed to be directly associated with a risk for adverse behavioral adaptation (e.g., Bjørnskau, 1994 as cited in Amundsen & Bjørnskau, 2003; Elvik, 2004; Hedlund, 2000), I tried to manipulate the safety of the adaptive warnings in Study 2. By introducing a steering wheel vibration condition and a brake jerk condition, drivers were supported differentially by the adaptive FCW during distraction. The brake jerk was supposed to provide a higher safety due to its ability to directly defuse situational criticality without driver input. However, drivers adapted their behavior when being provided with incorrect and unexpected support in distraction situation similarly in the steering wheel vibration and brake jerk condition. Different explanations may account for the finding that behavioral adaptation was independent from the manipulated safety effect associated with the distraction adaptive warnings. First, the manipulated objective safety difference between the warning conditions may have been too weak to be able to induce behavioral effects. Second, the results may further be related to the perceived safety of warnings. Next to the objective safety effect of a measure, this perceived effect poses a relevant influential factor for the emergence behavioral adaptations (e.g., OECD, 1990). Indeed, both the vibration warning and the brake jerk warning were rated

similarly useful and safe. As the presented manipulation of safety was not able to influence perceived safety of warnings in drivers, it may have been too weak to selectively influence driver behavior. Thus, this lack of effect can possibly be attributed to methodological issues. Further research should seek clarification whether the safety associated with the newly introduced function presents a risk factor for adverse behavioral effects.

In sum, explicit knowledge of system functioning seems to be relevant for the generation of expectancy. Based on identified tendencies regarding the overall safety estimates for future adaptive ADAS, one could predict adverse behavioral adaptation to be likely when drivers are able to form concrete expectancies regarding system behavior and thus adapt their behavior when they experience system failures. Given these adverse effects associated with unreliable adaptive systems, high levels of system reliability serve as a prerequisite for the introduction of adaptive warning systems. Therefore, real world implications derived from the results of this thesis include the need of robust algorithms that allow for a reliable detection of driver distraction. Moreover, the results of Study 3 suggest that adverse behavioral effects occur irrespective of system experience and do not exclusively become apparent in response to system failures. The present results however, do not allow for any firm conclusions regarding an overall prediction of safety associated with adaptive ADAS. Given that adverse behavioral adaptation effects may vary according to the setting (Saad, 2007) research on the actual effect on safety should further be investigated in a naturalistic driving setting. As adverse behavioral adaptations are expected to further vary according to exposure (Manser, Creaser, & Boyle, 2013; Martens & Jenssen, 2012; Saad, 2007; Sullivan, Flannagan, Pradhan, & Bao, 2016), longer driving periods have to be investigated to infer the impact of adaptive ADAS on daily driving.

Finally, an important practical implication is that it may prove to be useful to develop adaptive ADAS in which drivers do not explicitly become aware of the underlying dynamic adaptation process. This could be done via information policy regarding advertisements, instruction manuals or trainings. Finally, whereas I found no indications for implicit learning of system adaptivity, this might be possible in different contexts or for different forms of ADAS. This might occur when the contingency between the trigger mechanism (e.g., driver state) and the system behavior becomes obvious due to, e.g., clear and distinct trigger mechanisms, noticeable changes of warning parameters due to adaptation as well as long-term and frequent experience of adaptive behavior.

## User acceptance

Adaptive ADAS that adjust warning parameters according to the drivers' need for support are not only hypothesized to improve safety due to a compensation of impairments in distracted drivers, but also to improve system acceptance (Smith et al., 2009). Indeed, investigating the acceptance of ADAS is of utter importance as the demonstrated safety potential of reliable adaptive warnings directly depends on whether they are purchased and used. While the thesis specifically focused on the effectiveness of adaptive warnings and their potential for adverse effects, I further assessed whether drivers are willing to accept adaptive functions. In general, based on my findings, estimates concerning the acceptance of distraction adaptive warning signals are promising.

Study 1 showed that adaptive warning strategies that adjust modality and intensity according to whether the driver is distracted or not may be useful in preventing a warning dilemma. Indeed, acceptance ratings demonstrated that the adaptive warning strategy presented vibrotactile-auditory warnings with high perceived urgency to currently distracted drivers while presenting less annoying auditory warnings to currently undistracted drivers. Study 2 demonstrated better acceptance for adaptive relative to conventional non-adaptive FCW systems. After having used both an unreliable adaptive FCW that relied on a modality-based adaptation strategy and a non-adaptive FCW, drivers indicated that they found the adaptive FCW more useful while providing more security. These findings were supported by a strong preference for the adaptive relative to the non-adaptive FCW by over 85% of drivers because of its potential to support distracted drivers. However, it should be noted that incomprehensible system behavior may undermine the acceptance of adaptive warnings in drivers. First, participants in the same study reported the adaptive FCW behaved in a more underhanded manner than the non-adaptive FCW. Second, participants who preferred the non-adaptive over the adaptive FCW widely named concerns regarding the reliability of the adaptive FCWs. Third, results from Study 3 suggest that drivers would find it rather annoying if the adaptive FCW presented unreliable warnings. However, both the adaptive and the non-adaptive system had received similar high scores regarding perceived satisfaction and trust. Similarly, Study 3 showed the tendency that driving with an adaptive FCW that relied on a timing-based adaptation strategy was regarded safer and associated with less mental effort than driving with a non-adaptive FCW. Interestingly, this finding emerged despite the fact that drivers were not able to familiarize with the adaptive functionality as no brake events were triggered. Thus, drivers seem to have preferred the adaptive over the non-adaptive FCW based on the system information

provided by the instruction-manual. Results imply that the concept of warning parameter adjustment by means of adaptation strategies as well as the expected safety benefits due to distraction mitigation are generally understandable. Moreover, Study 3 also addressed subjective acceptance of the HMI design of adaptive FCWs. Findings show that drivers who were provided with direct feedback of the underlying adaptive warning strategy stated to be more wary of the adaptive system while at the same time reporting higher perceived security of the adaptive technology than drivers who received no such feedback.

In general, the findings of the thesis are in line with a previous study on the acceptance of adaptive ADAS that found higher acceptance ratings for an adaptive relative to a non-adaptive ACC (Hajek et al., 2013). Importantly, however, in this investigation drivers did not notice any difference between the two ACC versions and thus were not able to detect adaptive functioning of the ACC, but also preferred the adaptive version after they received further information on both functions. When relating available findings on acceptance to the presented results on adverse behavioral adaptations to adaptive warnings, a conflict becomes apparent. While drivers tend to prefer an adaptive system over a conventional, non-adaptive system when they are aware of the system's adaptive functioning, they tend to show adverse behavioral adaptation under exactly these conditions. Further research is needed to investigate how to resolve this conflict.

### **Methodological considerations for studying adaptive ADAS**

There are various methodological challenges regarding the investigation of adaptive ADAS and associated adverse behavioral adaptation effects. Due to the large number of research settings and tools for studying adaptive ADAS, the methodological considerations should be met in accordance with the actual research question.

A first methodological consideration concerns the choice of study setting. So far mainly instrumented vehicles (Fletcher & Zelinsky, 2007; Pohl et al., 2007) have been used to study adaptive ADAS that rely on real-time detection. While simulator studies allow for a highly controlled driving setting regarding road conditions, traffic and the presentation of specific maneuvers and thus high internal validity, real-world testing with an instrumented vehicle provides high external validity due to realistic driving. Even though real-time distraction detection algorithms, which represent the basis for adaptive ADAS, can generally be integrated in driving simulators and instrumented vehicles, in practice, such distraction detection algorithms usually use cameras and eye-trackers. However, these technologies are commonly

reported to be sensitive to variable lighting conditions and additional reflections (e.g., Holmqvist et al., 2011; Pohl et al., 2007). Thus, for research questions that specifically aim at testing driver reactions to a robust distraction adaptive ADAS, it is recommended to choose carefully controlled environments as can be found in simulator settings. In accordance with this argumentation, Study 3 investigated driver reactions to an adaptive ADAS based on a real-time distraction detection algorithm which monitored both driver's eye movements as well as their operations while interacting with the IVIS online in a dynamic driving simulator. Study results confirm that continuous detection of distraction using this algorithm was possible. Participants who received feedback about their distraction perceived the system to act in a clear and comprehensible manner. In sum, given that sensors were able to provide data at a sufficient quality in the respective experimental setting, the use of real-time algorithms presents a promising approach for testing distraction adaptive systems.

Another relevant question examines how adaptive ADAS can be studied when an online algorithm is either not available at all or not in sufficient quality. In such cases, wizard-of-oz techniques were used as a basis for ADAS adaptation (Hajek et al., 2013). Wizard-of-oz approaches, which are widely used in research on human-machine-interaction (see e.g., Dahlbäck, Jönsson, & Ahrenberg, 1993; Fitch, Bowman, & Llaneras, 2014; Habibovic, Andersson, Nilsson, Lundgren, & Nilsson, 2016), enable the driver to experience a functionality without any system implementation by instead utilizing human simulations. Thus wizard-of-oz techniques can be used for the evaluation of adaptive ADAS in many experimental settings, such as driving simulators and real-world environments. Regarding the use of a wizard-of-oz technique to simulate distraction adaptive system behavior, two different types of approaches can be distinguished. In the first approach, the experimenter tracks the driver by monitoring whether he is currently distracted from the driving tasks and then adapt system behaviors similar to the functioning of real-time algorithms. While there is a need of constant observation of the participant's behavior, this approach allows for flexible adjustment to different forms of distraction and is suitable for scenarios in which natural distraction behavior is recorded. The second approach relies on manipulating driver distraction, either indirectly through instructions or directly through the presentation of external sources of distraction. Examples are experimenter-induced conversations as used in Study 1 and an externally-paced menu task as used in Study 2. Utilizing this approach, highly controlled forms of distraction (such as manual, visual, cognitive), the degree of involvement and the duration of distraction can be established. Given that driver distraction is varied according to a programmed system behavior, this approach also allows for the presentation of unreliable system behavior at a fixed ratio. Utilizing

this technique to present incorrectly adjusted warnings in terms of false positive and false negative warnings at a predefined ratio in Study 1 and Study 2, it becomes evident that this method is useful due to practical reasons such as efficient study conduction and internal validity.

The driver's mental model of the system and its functioning influence both driver behavior and attitude during system-usage (Beggiato & Krems, 2013). In real-world conditions, drivers who use an activated ADAS may form a mental model of the system in different ways. First and directly, they may be able to explicitly experience the system's behavior in situations in which the system informs, warns the driver or takes control of the vehicle. Second and indirectly, they may have knowledge and expectations about the system and its functionality. Thus, from a methodological point of view, the experimental setting in terms of system exposure and instructions may influence the mental model which participants develop of the specific system. Depending on the type of evaluated assistance, experiences of system functioning may vary in frequency as there are systems that react frequently (e.g., blind spot assistant, adaptive cruise control) and rather infrequently (e.g., collision warning and avoidance systems, emergency assistant). In line with many conventional studies (e.g., Abe et al., 2002; Abe & Richardson, 2004; Biondi et al., 2017; Gray, 2011; Ho et al., 2006; Jamson, Lai, & Carsten, 2008; Kramer et al., 2007; Mohebbi et al., 2009; Scott & Gray, 2008), drivers in Study 1 and Study 2 experienced explicit system behavior of the FCW more frequently than one would expect in real driving in order to assure an adequate power to detect statistical differences. Moreover, this procedure provided sufficient exposure to the system in order to find stable behaviors, which are expected to occur after longer usage in real driving with the system activated. However, this warning procedure is criticized for its deficits in external validity as repeated exposure may alter driver reactions (see e.g., Aust, Engström, & Viström, 2013; Engström, Aust, & Viström, 2010; Lee et al., 2002). To address the influence of anticipated behaviors of adaptive ADAS and thus to provide an additional measure for driver reactions to systems that do not intervene as frequently, Study 3 adopted a method (Naujoks & Totzke, 2014) that made the driver anticipate that the ADAS was active or not without inducing any system relevant situations during the drive. The method was a useful tool to identify adverse behavioral effects in drivers as the anticipated behavior of an adaptive FCW as associated with riskier car-following. As both explicitly experienced and anticipated system behavior induced specific behavioral tendencies, it is useful to take into account both forms of measures. In sum, investigating driver reactions to both anticipated and experienced system behavior result in more holistic and robust evaluation of ADAS.

A final question concerns the applicability of adaptive strategies to different forms of ADAS. In line with Smith et al. (2009), Study 2 and Study 3 of this thesis adjusted warning parameters of a forward collision warning system. In addition, other studies focused on the adjustment of various other systems such as traffic sign warning systems (Fletcher & Zelinsky, 2007), lane departure warnings (Pohl et al., 2007) or ACC (Hajek et al., 2013) to driver distraction. Accordingly, it is suggested that the adaptivity approach could be applied to a large number of functions. Such functions may be able to offset distraction related deficits by providing information, warnings or even actively influencing vehicle control by taking over lateral or longitudinal vehicle guidance. However, certain functions do not appear to be adequate systems for adaptation. These may include functions that are individually adjustable by the driver or systems that specifically track other driver states such as drowsiness or physical damage. In this regard, more research is required to increase our insight into the usefulness of adaptivity in the context of different functions. Whereas the thesis focused on the adaptation according to driver distraction, further research should evaluate whether other interindividual and intraindividual factors such as emotional state, experience or personality traits, that are known to affect driving behavior, could be integrated as an input factor for ADAS parameterization. For example, Montgomery, Kusano, and Gabler (2014) indicate that it would be useful to adjust FCW timings to the demographics of the driver such as age and gender to reduce the interpretation of nuisance alarms while providing more efficient warnings as they found both women compared to men and drivers over 30 years of age compared to younger drivers to react significantly earlier in the risk of a frontal collision. First attempts to realize such adaptation strategies include the adjustment of warning parameters to driver uncertainty (Yan, Eilers, Baumann, & Luedtke, 2016), the driver's intention to brake (Diederichs, Schüttke, & Spath, 2015) and individual RTs (Jamson et al., 2008).

## Conclusion

The research in this doctoral thesis investigated the immediate and short-time effects of adaptive warning strategies with regard to both positive and potential adverse effects and thereby aimed at gaining further insight into the overall safety benefit associated with adaptive technologies. The present experiments focused on the effects of generic adaptive signals (Study 1), modality-based adaptation of FCWs (Study 2), and timing-based adaptation of FCWs (Study 3).

It was demonstrated that the investigated adaptation strategies have the potential to facilitate response timing of currently distracted drivers. Thus, the presentation of warning signals that were adjusted in timing and modalities were better able to offset this common deficit in distracted driving than conventional non-adaptive warning signals. Moreover, modality-based adaptation strategies were able to provide less annoying assistance to currently undistracted drivers while at the same time presenting urgent assistance to currently distracted drivers. Results further show that drivers were in favor of adaptive relative to non-adaptive systems, which indicates high acceptance rates for adaptive FCWs.

However, the results of all three experiments also show that drivers may adapt to adaptive warning strategies in ways that could undermine their safety when they are explicitly aware of the systems' adaptive functioning. In the current setting, drivers relied on the expected high support provided by the adaptive warning strategies during distraction. Thus, failures to present adequately strong support to distracted drivers led to clear impairments. Also driving performance decrements were found as drivers produced shorter following headways and reduced TTC values during anticipated usage of an adaptive FCW.

The design of adaptive warning signals presents a major future challenge for system designers, as this thesis found that the system and the driver may adapt to each other. Since explicit awareness of the system's adaptive functionality has been identified as an important factor affecting behavioral adaptation, the key to maintaining the positive effects of adaptive warnings may be to present adaptive technologies in a way that adaptive nature as well as the underlying functionality do not become apparent to the driver. Moreover, due to the adverse effects on both correctly and incorrectly adjusted warnings presented by an unreliable adaptive warning system, failures of the system should be minimized. Consequently, a reliable analysis of the driver's state needs to be ensured by future driver monitoring algorithms. While the present findings provide a basis for further investigations on adaptive technologies and potential risk factors that lead to adverse reactions to such systems, more research is required to increase our insight into the exact mechanisms of the interplay between adaptive technology and associated driver behavior. Future research on adaptive systems should take long-term effects and more realistic environments such as real-world driving into account. Importantly, crash risk estimates could identify the overall effect of adaptive technologies on safety.



## Contributions

Table declares the contributions to each of the presented studies. The order of authors represents the magnitude of their relative contribution.

| Study  | Idea/<br>experimental<br>design | Planning/<br>conduction | Data analysis | Writing    |
|--|---------------------------------|-------------------------|---------------|------------|
| Reinmueller, K., Koehler, L., & Steinhauser, M. (2018). Adaptive warning signals adjusted to driver passenger conversation: Impact of system awareness on behavioral adaptations. <i>Transportation Research Part F: Traffic Psychology and Behaviour</i> , 58, 242–252. | KR, MS, LK                      | KR                      | KR, MS        | KR, MS     |
| Reinmueller, K., & Steinhauser, M. (2019). Adaptive forward collision warnings: The impact of imperfect technology on warning effectiveness and acceptance. <i>Accident Analysis and Prevention</i> , 128, 217–229.  | KR, MS                          | KR                      | KR            | KR, MS     |
| Reinmueller, K., Kiesel, A., & Steinhauser M. (2019). Adverse behavioral adaptation to adaptive forward collision warning systems: An investigation of primary and secondary task performance. Manuscript submitted for publication.                                     | KR, MS, AK                      | KR                      | KR            | KR, MS, AK |

Abbreviations: AK= Andrea Kiesel, LK = Linda Koehler, MS = Marco Steinhauser, KR= Katharina Reinmueller

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