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

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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.

1. Introduction

Multiple advanced driver assistance systems (ADAS) such as forward collision warning (FCW) systems have been introduced into the market in recent years. While ADAS have been shown to improve road safety (e.g., Adell et al., 2011; Ben-Yaacov et al., 2002), new methods of driver monitoring offer further potentials for optimizing the parameterization of these systems. Driver monitoring technology based on in-vehicle sensors (Cai and Lin, 2007; Fletcher and Zelinsky, 2007; Liang et al., 2007; Masood et al., 2018; Mbouna et al., 2013; Sigari et al., 2013) allows for the acquisition of information about the driver and for predicting situations in which the driver needs additional assistance. Adaptive ADAS that use driver monitoring to dynamically gauge system behavior according to the driver´s current need for assistance have a great potential to better compensate for driver deficits than regular ADAS and to further improve safety and acceptance (Hajek et al., 2013; Smith et al., 2009). Even though sensor-based driver monitoring systems are market ready, it is still widely unclear how drivers deal with adaptive ADAS technology, especially if system behavior is unexpected due to failures of driver monitoring. The present study investigates whether an adaptive FCW can mitigate the effects of driver distraction, and whether drivers show behavioral adaptation, that is, whether unexpected system behavior leads to safety impairments because drivers rely on the expected support. These questions are addressed in two differentially designed adaptive FCWs to determine if system design has an impact on these effects.

It is widely known that driver distraction is associated with decreased performance in driving (e.g., Burns et al., 2002; Hancock et al., 2003; Horberry et al., 2006; Lee et al., 2001; Strayer et al., 2003; Strayer and Johnston, 2001) and significantly compromises the safety of the driver (see e.g., Dingus et al., 2006, 2016; Klauer et al., 2006). Today, modern vehicles are equipped with various ADAS, supporting

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the driver in different ways, e.g., by providing haptic or acoustic warnings to indicate a safety-critical situation (Mohebbi et al., 2009), or by taking direct influence on vehicle guidance to mitigate collision risk (Coelingh et al., 2010). While these conventional systems are usually not automatically adapted to changes in a driver's need for assistance (Hajek et al., 2013), current development focuses on adaptive ADAS providing drivers with user-centered support to mitigate the effects of interindividual deficits (Abe et al., 2011; Jamson et al., 2008) and distracted driving (e.g., Blaschke et al., 2009; Engström and Victor, 2009; Smith et al., 2009). According to Smith et al. (2009), these adaptive systems aim at optimizing the trade-off between safety and acceptance. Adaptive ADAS adjust their behavior according to the driver´s need and thus provide distracted drivers with additional assistance that has a better potential to compensate their deficits. At the same time, these systems are associated with higher acceptance than conventional systems as they provide not only efficient support to distracted drivers but also provide less intense and annoying support to undistracted drivers. Nevertheless, researchers raise the concern that utility of an intelligent and dynamically adjusting system could be undermined when the system behavior is regarded as inconsistent (Smith et al., 2009) or unpredictable (Engström and Victor, 2009).

First studies on adaptive ADAS achieved promising results. For example one study by Hajek et al. (2013) compared driver behavior between a standard ACC and an adaptive ACC that increased the distance from 1 to 2 s time to collision (TTC) according to the driver´s mental workload, thus giving a driver under high workload conditions more time to initiate an adequate reaction. In situations in which the ACC system´s limitations were reached and therefore drivers had to execute a brake reaction themselves, drivers using the adaptive ACC decelerated smoother and more safely than drivers using the conventional ACC. However, the study found no acceptance benefits for the adaptive over the conventional ACC when drivers remained unaware of the adaptive nature of the system but preferred the adaptive ACC if they were instructed about its functioning. Blaschke et al. (2009) identified improved driving performance for a lane departure warning (LDW) system that provided earlier support than a conventional LDW in distraction situations. In sum, these and other studies (Smith et al., 2009; Jamson et al., 2008) were able to identify safety benefits of adaptive ADAS over non-adaptive ADAS by compensating driver deficits.

However, the use of ADAS is not only accompanied by positive effects. Unwanted and unexpected consequences associated with the introduction of a new system or safety measure, are called behavioral adaptations (OECD, 1990). Investigating potential behavioral adaptation effects before introducing a new system into the market is crucial for the assessment of a system´s real safety potential. Different contributing factors for the development of adverse behavioral adaptations such as user personality (e.g., Jonah, 1997; Rudin-Brown and Parker, 2004; Weller and Schlag, 2004), system awareness and feedback (e.g., Grembek, 2010; Hedlund, 2000; OECD, 1990), or motivation (Hedlund, 2000; OECD, 1990; Weller and Schlag, 2004) have been identified in the last decades. Moreover, it is widely suggested that users are more likely to adapt their behavior to a measure the higher its objective effect (Bjørnskau, 1994, as cited in Amundsen and Bjørnskau, 2003; Elvik, 2004) and the associated perceived safety benefit (Bjørnskau, 1994, as cited in Amundsen and Bjørnskau, 2003; Elvik, 2004; OECD, 1990). Similarly, Hedlund (2000) states that adverse behavioral tendencies will only occur if the measure affects the user positively, e.g., by changing perceived risk and safety. Situations which are likely to be associated with adverse behavioral effects are system failures. Failures in conventional ADAS were found to result in more severe consequences than the absence of assistance. For example, failures of FCW systems to present adequate warnings in collision scenarios were associated with slower responses, more driving errors and less safe driving behavior than unassisted driving (e.g., Abe et al., 2002; Mahr et al., 2010). Similar findings have been reported for failures in ACC systems (e.g., Hogema and Janssen, 1996; Larsson et al., 2014; Nilsson, 1995). This research provides evidence that drivers form predictions and expectations about how the system will react and rely on them. This reliance then manifests in a decreased alertness, leading to impaired safety whenever the system fails.

In the context of adaptive ADAS, which are based on driver monitoring, a new form of system failure can occur. In addition to failures that lead to the full absence of support, failures of driver monitoring can result in too weak or too strong support when the driver monitoring falsely indicated the driver state. To the best of our knowledge, only one test-track study investigated driver reactions to failures of adaptive warnings signals (Reinmueller et al., 2018). In this study, drivers had to manually respond to a warning signal while driving, and the type of warning (auditory vs. visuohaptic-aditory) was dynamically adjusted according to whether the drivers were currently distracted by a conversation or not. Unexpected warnings resulted in adverse behavioral effects regarding driver responses: Clear reaction time (RT) decrements were found in situations in which the adaptive strategy failed and unexpectedly presented incorrect auditory warnings instead of visuohaptic-auditory warnings. However, these adverse effects were observed only if drivers were informed about the adaptive nature of the underlying warning strategy. The specific results indicated that these informed drivers allocate their attention away from the auditory warning whenever they expected additional visuohaptic support. No adverse behavioral adaptation effects were obtained in drivers who were unaware that warnings were adjusted depending on driver distractions. These findings are in line with theoretical assumptions about awareness as a risk factor for behavioral adaptation (e.g., Grembek, 2010; OECD, 1990; Rudin Brown and Parker, 2004).

To summarize, the usefulness of adaptive ADAS has been documented in first studies, but little is still known about the potential of adaptive ADAS to show adverse effects of behavioral adaptation. First, while studies on conventional ADAS were able to identify adverse behavioral adaptation when the system failed and provided no support at all, it remains unclear whether such effects also occur in adaptive ADAS when these erroneously present weak support to distracted drivers. So far, the only study in this context (Reinmueller et al., 2018) was limited as it did not include any hazards or critical scenarios, leaving open the question whether failures of adaptive ADAS result in safety-critical events also in more realistic scenarios. Second, there is a research gap regarding risk factors for behavioral adaptation. Knowledge about risk factors could inform system design, thus lowering the risk for behavioral adaptation when new ADAS are introduced. As behavioral adaptations are more likely in systems with greater safety benefit (e.g., Elvik, 2004; Hedlund, 2000), Donmez et al. (2003) suggested that system failures should result in more severe consequences in systems that intervene in vehicle control as compared to systems that only present warnings. It therefore remains to be investigated whether adverse behavioral effects in response to a system failure are more pronounced when drivers are supported by a more effective ADAS. Third, user acceptance for adaptive ADAS is assumed to be higher than for conventional ADAS (Smith et al., 2009) due to optimized assistance. However, previous research has not addressed how drivers accept an adaptive ADAS that obviously changes its behavior and occasionally even presents unreliable warnings.

1.1. Rationale of the study

The aim of the present study was to investigate the overall safety potential and the acceptance of an adaptive FCW. We address the potential for adaptive warnings to support a distracted driver while at the same time elucidating the role of expectancy, which accounts for observable adverse behavioral effects in situations in which the adaptive system fails. To this end, we conducted a driving simulator study in which drivers were periodically presented with a secondary task while following a lead vehicle. Drivers had to react to brake events of this vehicle that occurred in situations with and without distraction. Within this scenario, we compared an adaptive FCW with a non-adaptive standard FCW. While the non-adaptive FCW provided a visual warning irrespective of driver distraction, the adaptive FCW changed warning parameters and provided extra assistance in terms of an additional haptic warning component when drivers were distracted by secondary-task engagement. Moreover, we introduced two forms of adaptive FCWs that varied according to the presented haptic support: While 50% of participants received the haptic warning component in form of a steering-wheel vibration, the other 50% of participants received a brake jerk in distraction situations.

We hypothesized adverse behavioral adaptation effects to occur in response to situations in which the adaptive FCW system fails to provide visuo-haptic support and unexpectedly triggers visual warnings only. In these situations, visual warnings should result in slower reactions and, crucially, an increased criticality of the brake event compared with a non-adaptive FCW that correctly and expectedly presents visual warnings. We assumed that two effects would contribute to the outcome in these failures of the adaptive FCW: (1) the decreased ability of the visual warning to compensate the effects of distraction on criticality and driver reactions (compensation effect), and (2) the reliance of the driver on the expected visuo-haptic warning which affects criticality and driver reactions when an unexpected visual warning occurs (expectancy effect). Only the latter effect is truly indicative of behavioral adaptation. Based on the presumed relationship between safety benefits of a system and the risk of behavioral adaptation (Donmez et al., 2003; Elvik, 2004), we predicted the expectancy effects to vary as a function of support condition. Expectancy effects should be more pronounced in participants experiencing a brake jerk in the adaptive FCW than in participants experiencing a vibration warning. Furthermore, we analyzed the effectiveness of adaptive FCW to compensate the effects of distraction on criticality and driver reaction when correct warnings are triggered. Here, we expected correct warnings of an adaptive FCW to be more effective to reduce criticality than warnings of a non-adaptive FCW.

2. Method

2.1. Sample

Data were collected from 48 participants (20 males) ranging from 22 to 50 years of age (M = 32.0, SD = 8.3) who reported normal or corrected-to-normal vision. Participants were recruited from the driver panel of the Wuerzburg Institute for Traffic Sciences (WIVW) and compensated with 25 € for their participation. To minimize the risk of simulator sickness, all participants had received a simulator training before (Hoffmann and Buld, 2006). The study was conducted according to the Declaration of Helsinki and informed consent was obtained from each participant.

2.2. Driving simulator

The study took place in the motion-based driving simulator of the WIVW, which consists of a vehicle console with automatic transmission. The simulator has a 180° horizontal field of vision, visualized by three LED projectors in the dome. LCD displays served as rear view and outside mirrors. The motion system uses six degrees of freedom and consists of six electro pneumatic actuators. The simulation software framework SILAB developed by the WIVW GmbH (http://www.wivw.de) was used to simulate both environment and assistance systems. Gaze behavior (not reported here) was recorded with the Smart Eye AB eye tracker using four infrared cameras. Data were recorded with a sampling rate of 100 Hz.

2.3. Primary driving task and secondary distraction task

The driving task required participants to drive straight on a two-lane city ring with moderate traffic density following a lead vehicle. The lead vehicle moved with an average speed of 50 km/h and initiated brake events with a constant deceleration of $-6\ m/s^2$. The speed of the lead vehicle changed according to an alternating sine wave function with an amplitude of 6 km/h. To prevent a collision in brake events, drivers had to initiate a brake response. In line with research on brake reactions in both real-world and simulated driving contexts (e.g., Kiefer, 2000; Scott and Gray, 2008), the leading vehicle´s brake lights were switched off to prevent drivers from anticipatory brake reactions. To keep braking events constant across the experiment, participants were instructed to maintain a continuous time headway. Utilizing a procedure used in prior research on collision warnings (Gray, 2011; Ho et al., 2006; Mohebbi et al., 2009; Scott and Gray, 2008), a feedback was presented whenever participants fell behind the leading vehicle with a THW > 2 s. This feedback was presented visually by means of a blue strip displayed on the track.

While driving, an FCW system was active that protected against rear-end collisions by anticipating critical driving situations in front of the vehicle. In case of an acute risk of colliding with a leading vehicle, drivers were supported by the system. We tested two different versions of an FCW system. Both versions reacted as soon as the critical threshold of TTC = 4 s was reached in a brake event. On average, the time between lead vehicle braking and system reaction was 1.11 s (SD = 0.24 s). The two different FCW versions differed in their system behavior. The non-adaptive standard FCW triggered visual warnings irrespective of driver distraction thus using no driver monitoring information. The visual warning consisted of a red warning triangle presented on the cluster display. When operating correctly (see below), the adaptive FCW changed warning output according to driver distraction. In situations without distraction, the adaptive FCW triggered the visual warning described above. In distraction situations, the FCW presented visuo-haptic support by simultaneously triggering the visual warning and a haptic warning, which was a steering wheel vibration in half of the participants and a brake jerk in the remaining ones. The non-directional steering wheel vibration warning was realized by delivering pulse-like steering torques. The brake jerk was implemented as a short burst of deceleration and was presented for 275 ms in total with a peak deceleration of $-2.9\ m/s^2$. Crucially, warnings of the adaptive FCW were realized using a wizard-of-oz paradigm, i.e., warnings were not triggered based on the truly detected distraction state but according to the experimentally induced distraction state.

We induced distraction by means of a secondary task. Participants executed a continuous and highly demanding secondary task – the RSVP task (rapid serial visual presentation; Broadbent and Broadbent, 1987), which has previously been used in the driving context to induce distraction (e.g., Ho et al., 2005; Wiedemann et al., 2018). The choice of this secondary task was motivated by the need of a task that was externally paced to ensure predictable distraction situations. Drivers were instructed to complete the task as soon as it was presented by making as few errors as possible. The RSVP task involves the presentation of a stream of rapidly presented stimuli located on the lower half of the middle console. Participants had to identify number targets embedded in a stream of letter distractors. The stimulus set consisted of 18 different stimuli, four number targets (2, 3, 6, 9) and 14 letter distractors (B, C, D, E, F, J, K, L, M, N, P, R, Y, Z). The stimuli were randomly presented at a rate of 400 ms with an interstimulus interval of 100 ms. The target rate was 30%. Participants were instructed to press a key positioned at the arm rest immediately when they identified a target stimulus and to refrain from reacting when they detected a distractor. Visual feedback was provided for 400 ms on the same display in form of a green “o” for correct and a red “x” for incorrect reactions.

2.4. Procedure

At the beginning of the experimental session, participants completed a data privacy statement and received information about the objectives and procedure of the experiment. Then, they were allowed to get familiarized with the RSVP task and the scenario during a 5-min practice drive, during which no brake event occurred. This was followed by two experimental drives in which participants experienced the two different FCW versions. Half of the participants experienced the adaptive drive first and the other half experienced the non-adaptive drive first. Each participant was randomly assigned to one of the two orders. Before each experimental drive, participants received instructions about the FCW version they were about to encounter with the help of a user manual. During each drive, participants experienced brake events with and without distraction while being assisted with the respective FCW system. After each drive, subjective measures were assessed using a questionnaire. Participants took a break between the experimental drives and were free to take additional brakes during the experimental session.

The average duration of the experimental drives was about 20 min for the non-adaptive FCW and 40 min for the adaptive FCW. Fig. 1 depicts the structure of the two experimental drives. In order to assure consistent road layout and surrounding traffic over the experimental drives, a template road section was designed. Within each drive, participants experienced multiple sequences of this template section, with each section containing five randomly distributed brake events. As the drive with the non-adaptive FCW was shorter than the drive with the adaptive FCW, four and eight consecutive sections were used, respectively. During each drive, participants experienced sections with and without distraction, that is, with and without the secondary task. As the drive with the non-adaptive FCW was shorter than the drive with the adaptive FCW, we used a short and a long version of the same track for the respective drives. Driver distraction by means of the secondary task (undistracted vs. distracted) was alternated between the road segments, and the order of presentation was counterbalanced across participants. Each participants was randomly assigned to the order starting with the distracted condition or to the order starting with the undistracted condition. The same order was used for the non-adaptive and the adaptive FCWs.

The drive with the non-adaptive FCW contained a total of 20 brake events (10 in each distraction condition) in which always visual warnings were presented irrespective of driver state. The drive with the adaptive FCW contained 40 brake events (20 in each distraction condition). In 80% of brake events, correct warnings were provided, i.e., a visuo-haptic warning was provided when the driver was distracted but a visual warning was provided when the driver was undistracted. As the focus of this study was to identify behavioral reactions to imperfect adaptive technology, incorrect warning were provided in 20% of brake events, i.e., a visuo-haptic warning was provided even though the driver was undistracted, or a visual warning was provided when the driver was distracted. Together, this resulted in 16 correct warnings and 4 incorrect warnings in each distraction condition (see Table 1). Please note that as in both drives the number of brake events was evenly distributed across the distraction conditions, the brake event could not be predicted based on whether the driver was distracted or not. At the beginning of each experimental drive, we made drivers familiar with the system by conducting a brief training drive with four brake events and a perfectly reliable FCW. Please note that the experimental drive with the adaptive FCW was longer than that with the non-adaptive FCW. This was done to ensure that enough data from incorrect warning situations of the adaptive FCW were obtained while at the same time limiting the experimental session to a reasonable duration.

Based on the manipulations described above, we obtained a $2 \times 3 \times 2$ mixed factorial design with the variables Distraction (undistracted, distracted) and Warning (adaptive/visual, adaptive/visuo-haptic, non-adaptive/visual) as within-participants variables and Support (brake jerk, steering wheel vibration) as between-participants variable. Please note that this implies that each cell of the experimental design included the data of 24 participants.

2.5. Data analyses and dependent variables

Both objective and subjective data were assessed. Table 2 provides a summary of all objective measures. The criticality of the brake event as a measure of safety represents our main research interest and was assessed by two different TTC-based measures. TTC is the time until two vehicles collide if they remain on their paths and continue with their current speeds (Hayward, 1972). First, we examined the minimum TTC in each brake event, which provides information on how well participants reacted to the braking lead vehicle (Muhrer et al., 2012). We further measured the frequency of critical events by calculating the number of events, in which the critical threshold of TTC < 1 s was reached, divided by the total number of brakes. A threshold of 1 s was proposed by Hayward (1972) as an indicator of near-crashes. It is assumed to be a useful measure of serious conflicts (e.g., Sayed et al., 1994) and was employed in numerous previous studies (e.g., Naujoks et al., 2016; Naujoks and Totzke, 2014; Zegeer, 1977). As a further measure of the frequency of critical events, we counted the number of collisions which, however, were rather infrequent in our experiment. Furthermore, as the effect of an FCW is directly associated with the driver's response to the presented warnings (Montgomery et al., 2014), we further measured reaction times to quantify the effectiveness of the warnings triggered by the different FCW versions. We assessed the brake initiation RT to the onset of the warning output (Biondi et al., 2017; Gray, 2011; Ho et al., 2006; Lubbe, 2017). Finally, and in line with prior research, we assessed error rates for the RSVP task (Ho et al., 2005). This measure provides an indicator of secondary task engagement when interacting with different FCW systems[1] .

We also collected data from a number of subjective measures. After each experimental drive, questionnaires were completed to assess subjective acceptance and evaluation of the different FCW systems. We used the 5-point Van der Laan Scale (Van der Laan, Heino, & De Waard, 1997) to assess perceived usefulness of and satisfaction with the FCW versions. Moreover an evaluation of system, warning and driving was performed using an additional paper-pencil questionnaire (see Table 3). Trust in the FCW system was measured by several items of the one-dimensional scale for trust in automated systems (Jian et al., 2000) and participants had to indicate their agreement to the statements on a seven-point rating scale ranging from "not at all" to "completely". Items were selected according to whether they were considered useful in the context of FCW system use. For the evaluation of the warning modalities, participants were asked to rate warning helpfulness, annoyance, urgency, pleasantness and comfort. They responded to the five questions on a verbal-numeric scale with six verbal categories (no agreement, very low agreement, low agreement, medium agreement, strong agreement, very strong agreement), with all but the no agreement category divided into three numeric categories, resulting in a scale from 0 to 15. The same scale was used in the evaluation of the perceived safety and distraction from the driving task. An open question at the end of the experimental session assessed the driver´s intention to use.

3. Results

The focus of this study was to examine the safety potential of adaptive FCWs. We therefore analyzed the effects of warnings presented by adaptive FCWs on situational criticality and RT. We present

[1] In line with previous studies (Ho et al., 2005), we did not remove time periods with errors in the RSVP task when analyzing driving reactions. First of all, removing time periods with errors in the RSVP task is technically difficult, because it is unclear how much time around the errors should actually be removed. Second and most important, removing time periods around errors could bias the comparison between distracted and undistracted conditions because it is unclear why these errors are committed. For instance, if errors are caused by mind wandering, we would remove time periods with mind wandering from the distracted condition but not from the undistracted condition.

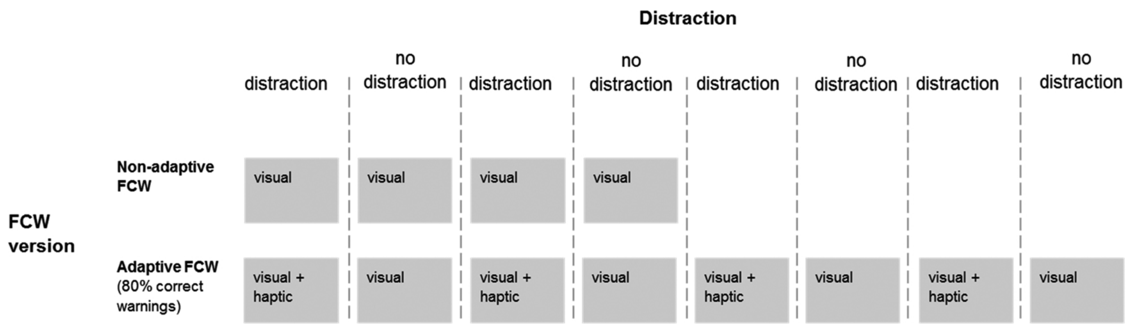

Fig. 1. Design and procedure of the simulator study. Each FCW version was used in one experimental drive. Within each experimental drive, the sequence of road sections (grey rectangles) is depicted. Please note that the road sections with and without distraction always alternated whereas the distraction condition of the first road segment was counterbalanced across participants.

Table 1
Description of system behavior of the non-adaptive and adaptive FCW as a function of driver distraction. Numbers in brackets indicate the number of trials (i.e., brake events) participants experienced in the respective condition.

		System behavior			
		Distracted driver		Undistracted driver	
FCW version	Non-adaptive FCW	Visual (20)		Visual (20)	
	Adaptive FCW	Visual + Haptic (16, correct warnings)	Visual (4, incorrect warnings)	Visual (16, correct warnings)	Visual + Haptic (4, incorrect warnings)

Table 2
Overview of the objective dependent measures.

Construct	Dependent Measure	Unit
Criticality of the brake events	Minimal TTC: Minimum time-to-collision to the leading vehicle in the brake events	s
	Frequency of critical events with a TTC < 1 s	%
	Number of collisions	–
Reaction time	Brake initiation reaction time to the warning output	ms
Secondary task engagement	RSVP error rate	%

Table 3
Overview of items used for evaluation of trust in the systems, warning modalities and perceived driving safety.

Construct	Item
Trust (Jian et al., 2000; German translation as used in Beggiato et al., 2015)	The system is deceptive
	The system behaves in an underhanded manner
	I can trust the system
	The system provides security
	The system is reliable
Evaluation of warning modalities	The warning was helpful
	The warning was pleasant
	The warning was urgent
	The warning was annoying
Driving safety (adapted from Harbluk et al., 2007)	I felt safe during the drive
	I felt distracted from the driving task
Intention to use	Which of the two variants would you prefer in your own vehicle for every day driving?

the data in the following way: In a first step we investigate the risk of an adaptive FCW to induce behavioral adaptation effects by focusing on the effects associated with system failures. In a second step, we examine the warning effectiveness of an adaptive FCW relative to a standard non-adaptive FCW. Here, we investigate whether the adaptive FCW is able to offset deficits of distracted drivers better than a non-adaptive standard FCW system when correct warnings are provided. In a third step, we present the number of collisions that occurred in drives with the adaptive and non-adaptive FCW. In a fourth step, we present RSVP data to examine whether participants changed their engagement in the secondary task according to the use of different FCW systems. In a final step, we present subjective data.

3.1. *Expectancy vs. compensation*

The adaptive FCW presented warning modalities (visual and visuo-haptic) as a function of driver distraction (undistracted, distracted), while the non-adaptive standard FCW presented visual warnings only. Moreover, one group received a brake jerk as visuo-haptic warning, while the other group received a steering wheel vibration. To analyze behavioral adaptation effects, we compared the criticality measures and driver reactions between the adaptive FCW and the non-adaptive standard FCW. In general, we expected performance to decrease when incorrect visual warnings are triggered by the adaptive FCW in distraction situations (see Fig. 2). Such a result potentially reflects the combined effects of two variables: a) The *compensation* of distraction by the supportive visuo-haptic warning, which is omitted when an incorrect visual warning is presented. b) The *expectancy* of the driver to receive a visuo-haptic warning in case of distraction, which makes drivers to rely on this supportive warning, thus inducing additional decrements when the warning is less supportive. Only the latter effect represents an adverse effect of behavioral adaptation. Fig. 2 illustrates the hypothesized contribution of expectancy and compensation to the result pattern. To disentangle the contribution of these two effects to our data, the following three-step analysis strategy was applied to each dependent variable:

(1) Omnibus analysis: We conducted a 2x3x2 ANOVA with the within-participant variables Distraction (undistracted, distracted) and

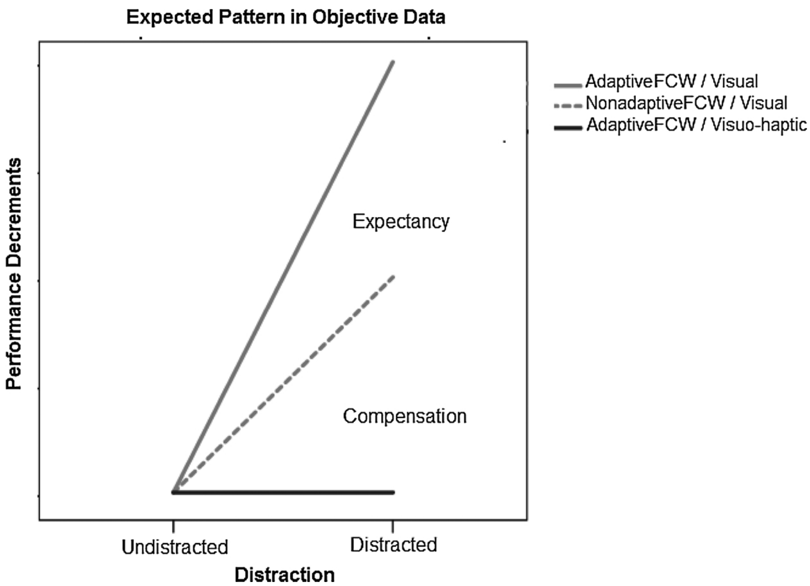

Fig. 2. Expected pattern in objective data. Incorrect warnings (adaptive FCW/visual in distracted drivers) should be associated with performance decrements, and this effect should be due to an expectancy effect and a compensation effect. The expectancy effect can be isolated by contrasting visual warnings for distracted drivers in adaptive and standard non-adaptive FCWs. The compensation effect can be isolated by contrasting expected visual warnings in non-adaptive FCWs and expected visuo-haptic warnings in adaptive FCWs. FCW = forward collision warning.

Warning (adaptive/visual, adaptive/visuo-haptic, non-adaptive/visual) and the between-participant variable Support (brake jerk, vibration) to reveal the total effect of each variable. Only if we obtained a significant effect involving the variable Warning, the following follow-up analyses were conducted to isolate the effects of expectancy and compensation.

(2) Expectancy analysis: A 2x2x2 ANOVA with the variables Distraction (undistracted, distracted) and Warning (adaptive/visual, non-adaptive/visual) and Support condition (brake jerk, steering wheel vibration) was conducted to isolate the effect of expectancy. This analysis allows to compare situations which differ in the expectancy of visual warnings (adaptive/visual with distraction vs. non-adaptive/visual with distraction) while holding the type of warning and distraction constant. Please note that this rationale only holds for the distracted condition, whereas the adaptive/visual vs. non-adaptive/visual without distraction did not differ with respect to expectancy. A pure effect of expectancy would thus result in an interaction between Distraction and Warning in the ANOVA.

(3) Compensation analysis: A 2x2x2 ANOVA with the variables Distraction, Warning (adaptive/visuo-haptic, non-adaptive/visual) and Support was conducted to isolate the effect of compensation. This analysis allows to compare situations which differ in the effect of compensation (adaptive/visuo-haptic with distraction vs. non-adaptive/visual with distraction) while holding the expectancy of receiving a particular warning as well as distraction constant. Again, this rationale only holds for the distracted condition as, without distraction, the adaptive/visuo-haptic condition was additionally unexpected, thus confounding expectancy and compensation.

In all analyses, the variable Support is included to examine whether compensation and expectancy vary as a function of support. Following the rationale outlined in the introduction, we hypothesized both expectancy and compensation effects to be more pronounced in the brake jerk group than in the vibration group.

3.1.1. Criticality: minimal TTCs

Criticality measures (minimal TTCs and proportion of critical TTCs) are the primary dependent variables in our study as they represent direct indicators of the safety outcome in a braking event. Fig. 3 depicts the results for the minimal TTCs. The omnibus analysis revealed a significant main effect of Distraction, $F(1, 46) = 75.80$, $p < .001$, $\eta^2_{partial} = 0.62$, and a marginally significant main effect of Warning, $F(2, 92) = 15.80$, $p < .001$, $\eta^2_{partial} = 0.26$. We further obtained a significant interaction between Distraction and Warning, $F(2, 92) = 7.40$, $p < .01$, $\eta^2_{partial} = 0.14$. There were no further significant main or interaction effects, all $Fs < 1$.

The expectancy analysis revealed significant main effects for Distraction, $F(1, 46) = 75.91$, $p < .001$, $\eta^2_{partial} = 0.62$, and Warning, $F(1, 46) = 14.42$, $p < .001$, $\eta^2_{partial} = 0.24$, but no further effects ($Fs < 1$). Crucially, smaller minimal TTCs were obtained when participants received visual warnings from the adaptive (M = 1.75, SE = 0.04) compared to the non-adaptive FCW (M = 1.84, SE = 0.05), thus indicating an expectancy effect.

The compensation analysis revealed significant main effects of Distraction, $F(1, 46) = 74.50$, $p < .001$, $\eta^2_{partial} = 0.62$, and Warning, $F(1, 46) = 4.76$, $p = .034$, $\eta^2_{partial} = 0.94$, but again no further significant effects (all $Fs < 1.3$). Distracted and undistracted drivers benefitted from the visuo-haptic warnings in the adaptive FCW (M = 1.93, SE = 0.06) relative to the visual warnings in the non-adaptive FCW (M = 1.84, SE = 0.05), as indicated by higher minimal TTCs in the former.

3.1.2. Criticality: proportion of critical events

Fig. 4 depicts the results for the proportion of critical events representing the mean proportion of events with a TTC < 1 s. The omnibus analysis revealed significant main effects of Distraction, $F(1, 46) = 15.80$, $p < .01$, $\eta^2_{partial} = 0.26$, and Warning, $F(2, 92) = 16.68$, $p < .001$, $\eta^2_{partial} = 0.27$, and these effects were further qualified by a significant interaction between Warning and Distraction, $F(2, 92) = 7.40$, $p < .01$, $\eta^2_{partial} = 0.14$. There was no further significant main effect or interaction ($Fs < 1$).

The expectancy analysis revealed significant main effects of Distraction, $F(1, 46) = 15.64$, $p < .001$, $\eta^2_{partial} = 0.25$, and Warning, $F(1, 46) = 17.03$, $p < .001$, $\eta^2_{partial} = 0.27$, which were further qualified by a significant interaction between both variables, $F(1, 46) = 5.93$, $p = .019$, $\eta^2_{partial} = 0.11$. No other effects were significant ($Fs < 1$). Planned contrasts demonstrate that distracted participants experienced significantly more critical events when visual warnings were triggered by the adaptive FCW than when they were triggered by the non-adaptive FCW, $t(47) = 3.73$, $p = .001$, $d = 1.09$, whereas this effect was less pronounced for undistracted participants, $t(47) = 1.93$, $p = .06$, $d = 0.56$. These results demonstrate an expectancy effect, as visual warnings presented by the adaptive FCW led to an increased proportion of critical events relative to visual warnings presented by the non-adaptive FCW in distraction situations.

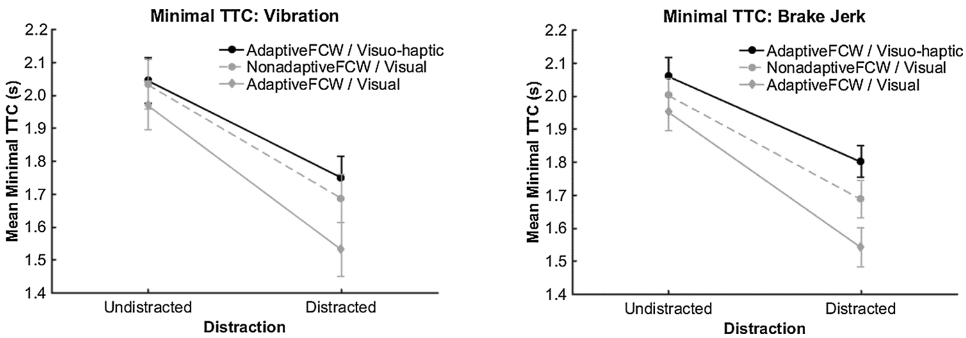

Fig. 3. Averaged minimal TTCs for visuo-haptic warnings of the adaptive FCW and visual warnings of both the adaptive and the non-adaptive FCW as a function of driver distraction. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Bars represent within-subject standard errors of the mean (Cousineau, 2005). FCW = forward collision warning, TTC = time to collision, s = seconds.

The compensation analysis revealed a significant main effect of Distraction, $F(1, 46) = 7.63$, $p = .008$, $\eta^2_{partial} = 0.14$, which was further qualified by a marginally significant interaction between Distraction and Warning, $F(1, 46) = 3.09$, $p = .085$, $\eta^2_{partial} = 0.06$. Planned contrasts revealed a marginally significant difference between the visuo-haptic warnings presented by the adaptive FCW and the visual warnings presented by the non-adaptive FCW, only for distracted, $t(47) = 1.91$, $p = .06$, $d = 0.56$, but not for undistracted drivers, $t(47) = 0$, $p = .1$, $d = 0$, which suggests a trend towards a compensation effect.

3.1.3. Reaction times

Fig. 5 depicts the results for the mean RTs in braking events. The omnibus analysis revealed significant main effects of Distraction, $F(1, 46) = 285.47$, $p < .001$, $\eta^2_{partial} = 0.86$, and Warning, $F(2, 92) = 7.61$, $p = .001$, $\eta^2_{partial} = 0.14$, and these main effects were qualified by a significant interaction between Distraction and Warning, $F(2, 92) = 12.95$, $p = .001$, $\eta^2_{partial} = 0.22$. No other effects were significant ($Fs < 1$).

The expectancy analysis revealed significant main effects of Distraction, $F(1, 46) = 247.77$, $p < .001$, $\eta^2_{partial} = 0.84$, and Warning, $F(1,46) = 5.31$, $p = .026$, $\eta^2_{partial} = 0.10$. Furthermore, a marginally significant interaction between both variables was obtained, $F(1,46) = 3.93$, $p = .053$, $\eta^2_{partial} = 0.08$. Other effects failed to reach significance, $Fs < 1$. Planned contrast demonstrated a significant RT slowing when distracted drivers receive a visual warning from the adaptive compared to the non-adaptive FCW, $t(47) = 2.49$, $p < .05$, $d = 0.73$, but not when the driver was undistracted, $t(47) = 1.07$, $p = .29$, $d = 0.31$, which demonstrates a clear expectancy effect.

The compensation analysis revealed a significant main effect of Distraction, $F(1, 46) = 298.27$, $p < .001$, $\eta^2_{partial} = 0.87$, which was further qualified by a significant interaction between Distraction and Warning, $F(1, 46) = 13.63$, $p = .001$, $\eta^2_{partial} = 0.23$. Moreover, we found a marginally significant interaction between Warning and Support, $F(1, 46) = 3.36$, $p = .08$, $\eta^2_{partial} = 0.07$. No other effects were significant ($Fs < 1.8$). Planned contrasts revealed that the RT difference between visuo-haptic warnings and visual warnings was found in distraction situations, $t(47) = 11.01$, $p < .001$, $d = 3.21$, but not in situations without distraction, $t(47) = 1.07$, $p = .29$, $d = 0.31$. Again, this indicates a compensation effect.

3.2. Warning effectiveness

The previous analyses aimed to isolate the contribution of expectancy and compensation to criticality and RTs in case of a system failure. In the next analysis, we investigated the effectiveness of the adaptive FCW to support drivers when correct warnings were elicited. To investigate which system generally evokes faster reactions and safer outcomes, for each objective measure, we calculated three-way ANOVAs including the variables Distraction (undistracted, distracted), Adaptivity (non-adaptive FCW, adaptive FCW) and Support (vibration, brake jerk). Importantly, for the adaptive FCW only braking events with correctly triggered warnings were considered. Please note that this analysis uses data that have already been reported in the previous section but applies a different analysis design. In this analysis, distraction and warning modality (visual vs. visuo-haptic) are naturally confounded for the adaptive FCW. However, we are interested in the overall effect of the system irrespective of whether these effects are caused by compensation or expectancy effects.

3.2.1. Criticality: minimal TTCs

Fig. 6 depicts the averaged minimal TTCs for this analysis. The ANOVA revealed a significant main effect of Distraction, $F(1,46) = 49.70$, $p < .001$, $\eta^2_{partial} = 0.52$, which was qualified by a significant interaction between Adaptivity and Distraction, $F(1,46) = 13.33$, $p = .001$, $\eta^2_{partial} = 0.23$. There were no other significant main effects or interaction effects ($Fs < .2.3$). There was a significantly higher minimum TTC in situations with distraction than in situations without distraction for the non-adaptive FCW, $t(47) = 7.76$, $p < .001$, $d = 2.26$. This effect was less pronounced for the adaptive FCW, $t(47) = 3.75$, $p < .001$, $d = 0.98$. This shows that the adaptive system partially compensated the effect of distraction on RTs.

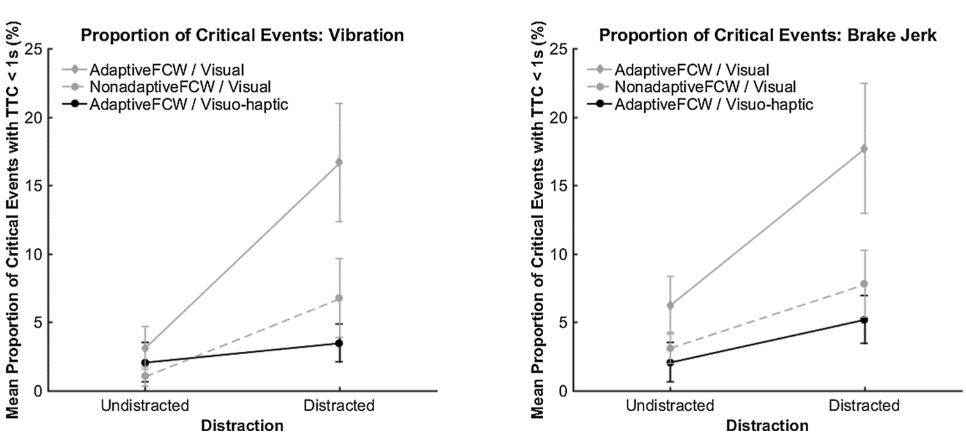

Fig. 4. Mean percentage of braking events that turn into critical scenarios according to the criterion of a TTC < 1 s for visuo-haptic warnings of the adaptive FCW as well as visual warnings of both the adaptive and non-adaptive FCW as a function of driver distraction. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Bars represent within-subject standard errors of the mean. FCW = forward collision warning, TTC = time to collision, s = seconds.

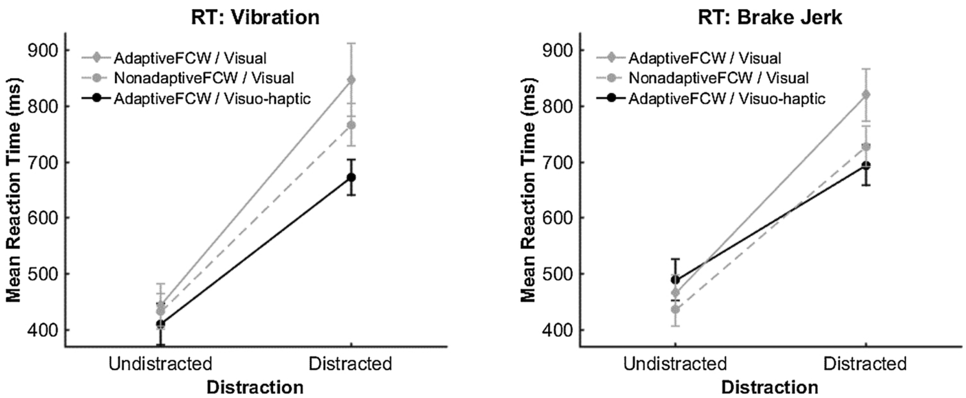

Fig. 5. Averaged RTs from warning output for visuo-haptic warnings of the adaptive FCW as well as visual warnings of both the adaptive and the non-adaptive FCW as a function of driver distraction. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Bars represent within-subject standard errors of the mean. FCW = forward collision warning, RT = reaction time, ms = milliseconds.

3.2.2. Criticality: proportion of critical events

Fig. 7 shows the proportion of critical events with a TTC < 1. We found a marginally significant main effect for distraction, $F(1,46) = 3.36$, $p = .073$, $\eta^2_{\text{partial}} = 0.07$. It was qualified by a significant interaction which revealed that the impact of distraction changed with adaptivity, $F(1,46) = 11.20$, $p = .002$, $\eta^2_{\text{partial}} = 0.20$. No other main or interaction effects reached significance (Fs < 1.2). The effect of distraction was significant for the non-adaptive FCW, $t(47) = 2.75$, $p < .01$, $d = 0.80$, but not for the adaptive FCW, $t(47) = 0.31$, $p = .78$, $d = 0.09$, again indicating that the adaptive FCW fully compensated the effect of distraction on criticality.

3.2.3. Reaction times

Fig. 8 shows the mean RTs. We obtained a significant main effect of distraction, $F(1,46) = 320.94$, $p < .001$, $\eta^2_{\text{partial}} = 0.88$, which was further qualified by a significant interaction of the variables Distraction and Adaptivity, $F(1,46) = 15.66$, $p < .001$, $\eta^2_{\text{partial}} = 0.25$. There were no further significant main or interaction effects (*F*s < 1.5). The difference in RTs between situations with and without distraction was more pronounced in the non-adaptive FCW compared to the adaptive FCW. However, the effect of distraction was still significant in the adaptive FCW, $t(47) = 14.15$, $p < .001$, $d = 4.13$, suggesting that the adaptive FCW only partially compensated the effect of distraction on RTs.

3.3. Collisions

Table 4 reports the number of collisions as a function of Distraction (undistracted, distracted) and Adaptivity (adaptive FCW, non-adaptive FCW) and the between-participant variable Support (brake jerk, vibration). Both reactions to correct and incorrect warnings are reported. We observed a total of eleven collisions only that were mainly caused in distraction situations in which participants were supported by a visual warning. Due to this small number, we refrained from analyzing these data statistically.

3.4. Secondary task engagement

To quantify performance in the RSVP task, we calculated mean error rates which considered both false positives and false negatives. The ANOVA with the variables Adaptivity (adaptive FCW, non-adaptive FCW) and Support (brake jerk, vibration) revealed a marginally significant main effect of System, $F(1,46) = 3.82$, $p = .057$, $\eta^2_{\text{partial}} = 0.77$, which implies that participants increased their engagement in the secondary task according to the use of different FCW versions. Error rates were 19.7% (SE = 2.5) for the non-adaptive and 18.0% (SE = 2.9) for the adaptive FCW system in the brake jerk condition and 18.9% (SE = 2.8) for the non-adaptive and 17.0% (SE = 3.0) for the adaptive FCW system in the vibration condition. There was no significant main effect of support condition or interaction effect, *F*s < a1.

3.5. Subjective assessment: usefulness and satisfactory

To assess the participants´ subjective evaluation of the FCW versions, we conducted separate ANOVAs with the variables System (adaptive FCW, non-adaptive FCW) and Support (brake jerk, vibration) for the usefulness and satisfactory dimensions (ranging from -2 to 2) of the van der Laan Acceptance Scale. Participants rated the adaptive FCW as more useful (M = 0.75, SE = 0.14) than the non-adaptive FCW (M = 0.09, SD = 0.15), $F(1, 46) = 19.32$, $p < .001$, $\eta^2_{\text{partial}} = .30$. However, the systems did not differ regarding the satisfactory dimension ($F < 1.8$), and both the adaptive FCW (M = 0.73, SE = 0.12) and the non-adaptive FCW (M = 0.56, SE = 0.12) were rated as quite

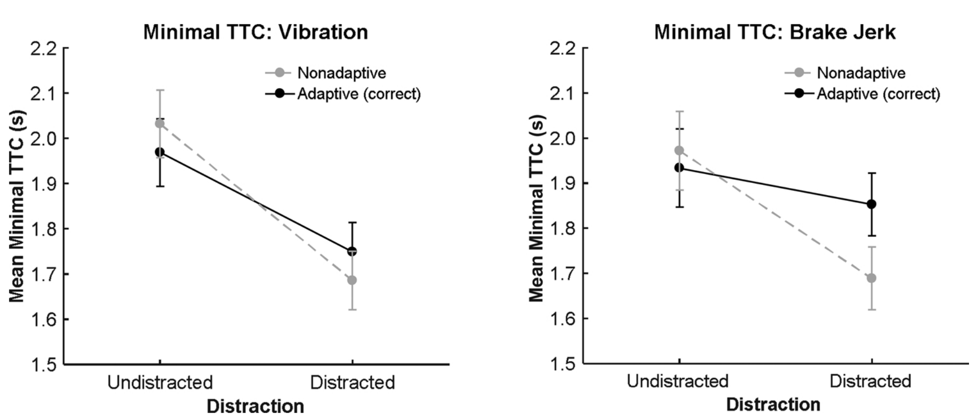

Fig. 6. Averaged minimal TTC during brake events with correct warnings as a function of driver distraction and adaptivity. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Bars represent within-subject standard errors of the mean. TTC = time to collision, s = seconds.

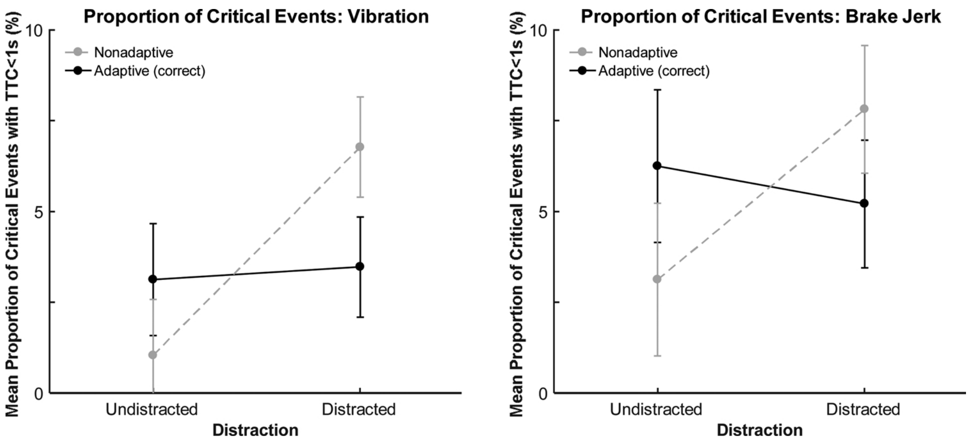

Fig. 7. Averaged proportion of critical brake events with correct warnings that fell below a TTC of 1 s in percent as a function of driver distraction and adaptivity. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Overall means are presented in the right panel. Bars represent within-subject standard errors of the mean. TTC = time to collision, s = seconds.

satisfactory. There were no other main or interaction effects (*Fs* < 2.8).

3.6. Subjective assessment: warning modalities

Means and SEs for all items are presented in Table 5. We investigated how participants rated the experienced FCW versions with respect to the subjective helpfulness, urgency, annoyance and pleasantness on a 16-point scale ranging from not agree at all to agree strongly (see procedure in Reinmueller et al., 2018). All items were subjected to two-way ANOVAs with the variables Modality (haptic, visual) and Support (brake jerk, vibration). While only significant results are presented in the following, an overview of all effects is shown in Table 6. We found that irrespective of support condition, the haptic warning was rated significantly more helpful than the visual warning, $F(1, 46) = 36.43$, $p < .001$, $\eta^2_{partial} = 0.44$. Moreover, the haptic warning was rated more urgent than the visual warning, $F(1, 46) = 41.48$, $p < .001$, $\eta^2_{partial} = 0.47$. Interestingly, there was a significant interaction between Support and Modality in the analysis of annoyance, $F(1, 46) = 5.18$, $p = .028$, $\eta^2_{partial} = 0.10$, which implies that the brake jerk was rated more annoying than the visual warning, while the vibration warning was not rated different than the visual warning. Generally, participants found all types of warnings medium pleasant.

3.6.1. Subjective assessment: perceived driving safety

The same analysis for driving safety revealed that participants agreed medium strongly that they felt safe during the drive when they used the adaptive FCW and less so when they used the non-adaptive version, $F(1, 46) = 13.08, p = .001, \eta^2_{partial} = .22$. No other effects were significant (*Fs* < 1.8). The extent to which participants felt distracted during driving did not differ according to either the experienced FCW version nor the support conditions as main and interaction effects failed to reach significance, *Fs* < 2.3. In general, participants strongly agreed to the statement “I felt distracted from the driving task”.

Table 4
Number of overall collisions grouped by distraction, FCW version and support condition.

		Number of overall collisions across all participants				
		Total	Undistracted		Distracted	
			Visual Warning	Visuo-haptic Warning	Visual Warning	Visuo-haptic Warning
Adaptive FCW	Brake Jerk	3	0	0	2	1
	Vibration	1	0	0	1	0
Non-adaptive FCW	Brake Jerk	4	2	–	2	–
	Vibration	3	0	–	3	–

3.6.2. Subjective assessment: trust

Finally, drivers rated on multiple items how much they trusted the FCW systems. While both the non-adaptive and adaptive FCWs were considered as only little deceptive (with no significant difference between both systems, $F < 1.6$), we found that the extent to which the system was believed to behave in an underhanded manner was larger in the adaptive FCW than in the non-adaptive FCW, $F(1, 46) = 6.83$, $p = .012$, $\eta^2_{partial} = .13$. Interestingly, participants agreed medium strongly that they could trust the systems (with no significant difference between both systems, $F < 1$) and also widely agreed that both FCW versions were similarly reliable ($F < 1.3$). A significant difference between the adaptive and the non-adaptive FCW version was obtained when participants were asked whether “the system provides security”. Here, they provided low to medium agreements, which were higher for

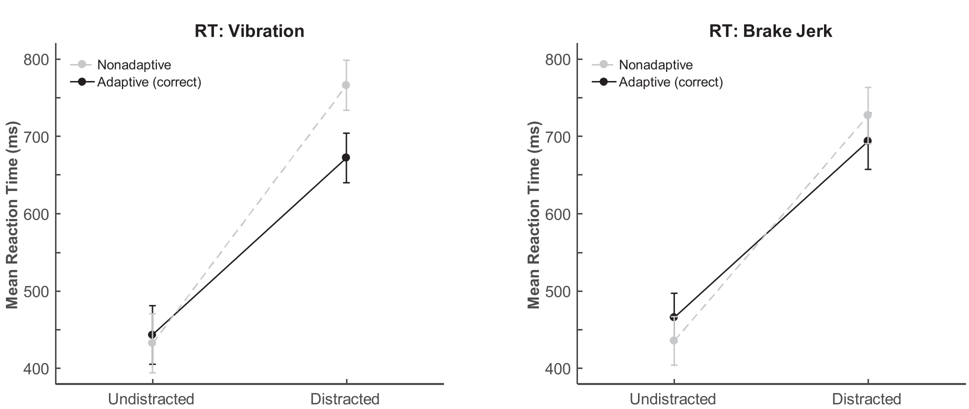

Fig. 8. Averaged brake RT from warning output as a function of driver distraction and adaptivity. The vibration condition is presented in the left panel, the brake jerk condition in the right panel. Overall means are presented in the right panel. Bars represent within-subject standard errors of the mean. RT = reaction time, ms = seconds.

Table 5
Descriptive statistics of follow-up interviews for each tested condition.

		Visual		Haptic	
		Brake jerk	Vibration	Brake Jerk	Vibration
Subjective warning evaluation (16-point scale)	The warning was helpful	M = 6.71 SE = 1.03	M = 8.88 SE = 0.87	M = 10.63 SE = 0.90	M = 11.79 SE = 0.48
	The warning was pleasant	M = 8.79 SE = 0.81	M = 9.46 SE = 0.72	M = 9.21 SE = 0.94	M = 11.13 SE = 0.62
	The warning was urgent	M = 6.13 SE = 0.93	M = 6.04 SE = 0.89	M = 10.08 SE = 0.90	M = 9.29 SE = 0.84
	The warning was annoying	M = 1.54 SE = 0.53	M = 1.42 SE = 0.53	M = 2.92 SE = 0.63	M = 0.88 SE = 0.26

		Adaptive		Non-adaptive	
		Brake Jerk	Vibration	Brake Jerk	Vibration
Perceived driving safety (16-point scale)	I felt safe during the drive	M = 8.08 SE = 0.84	M = 8.79 SE = 0.69	M = 5.83 SE = 0.63	M = 7.46 SE = 0.69
	I felt distracted from the driving task	M = 12.04 SE = 0.47	M = 12.42 SE = 0.54	M = 12.33 SE = 0.42	M = 11.96 SE = 0.60
Trust (7-point scale)	The system is deceptive	M = 2.04 SE = 0.28	M = 2.04 SE = 0.34	M = 2.00 SE = 0.26	M = 1.54 SE = 0.22
	The system behaves in an underhanded manner	M = 2.33 SE = 0.31	M = 2.38 SE = 0.37	M = 1.82 SE = 0.20	M = 1.71 SE = 0.24
	I can trust the system	M = 4.50 SE = .0.39	M = 4.63 SE = 0.39	M = 4.13 SE = 0.35	M = 4.71 SE = 0.34
	The system provides security	M = 4.29 SE = 0.44	M = 5.04 SE = 0.33	M = 3.47 SE = 0.40	M = 4.50 SE = 0.34
	The system is reliable	M = 5.13 SE = 0.28	M = 4.54 SE = 0.35	M = 5.01 SE = 0.23	M = 5.14 SE = 0.21

Table 6
Warning signal evaluation, ANOVA results. Bold letters indicate significant effects, $p < .005$.

Items	Effect	F	df1	df2	p	$\eta^2_{partial}$
The warning was helpful	**Modality**	**36.43**	**1**	**46**	**< .001**	**0.442**
	Support Condition	1.35	1	46	.250	0.029
	Interaction	0	1	46	1	0
The warning was urgent	**Modality**	**41.48**	**1**	**46**	**< .001**	**0.474**
	Support Condition	0.15	1	46	.700	0.003
	Interaction	0.40	1	46	.530	0.009
The warning was annoying	Modality	0.98	1	46	.328	0.021
	Support Condition	3.48	1	46	.069	0.070
	Interaction	**5.18**	**1**	**46**	**< .05**	**0.101**
The warning was pleasant	Modality	2.46	1	46	.124	0.051
	Support Condition	2.14	1	46	.150	0.044
	Interaction	0.88	1	46	.352	0.019

the adaptive FCW than for the non-adaptive FCW, $F(1, 46) = 8.09$, $p = .007$, $\eta^2_{partial} = .15$.

3.6.3. Subjective assessment: intention to use

In general, the majority of participants preferred the adaptive over the non-adaptive system, χ^2 $(1,\ n = 48) = 19.09$, $p < .001$). The adaptive FCW was preferred by 19 of 24 drivers in the brake jerk group and by 22 of 24 participants in the vibration group. Most frequent reasons reported by the supporters of the non-adaptive FCW were the triggering of too strong support in distraction situations and the unreliability of the adaptive FCW.

4. Discussion

The study investigated whether adverse behavioral adaptation tendencies can be found if an adaptive ADAS fails to provide the expected support. We therefore introduced adaptive FCWs that adjusted support according to driver distraction and investigated situations in which currently distracted drivers are provided with less support than expected due to a simulated failure in detecting the driver state. Driver behavior and criticality were compared between an adaptive FCW and a non-adaptive FCW. Moreover, we investigated these effects for two differentially supportive adaptive FCWs: The more supportive adaptive FCW presented an additional brake jerk and the less supportive adaptive FCW triggered an additional steering wheel vibration during driver distraction. This manipulation allowed us to further investigate whether a driver´s reliance on the adaptive FCW and therefore adverse behavioral effects increase with the potential of an adaptive FCW to support safe driving in distracted drivers.

First, as hypothesized, we found evidence for *expectancy effects* and therefore behavioral adaptation in situations in which the adaptive FCW failed in distracted drivers. Crucially, while both the presented warning and the distraction state were exactly the same, distracted drivers reacted slower, experienced higher situational criticality and a higher frequency of critical near-crash situations when a visual warning was triggered unexpectedly by the adaptive FCW than when it was triggered as expected by the non-adaptive FCW. These findings might reflect that drivers relied on the expected haptic support when the adaptive FCW was activated, and thus tended to allocate fewer resources to the processing of the visual warning. These safety decrements in the absence of expected support are in line with results from previous studies on conventional ADAS (e.g., Abe et al., 2002). Furthermore, our findings also confirm previous research on behavioral adaptations in manual reactions to warning signals (Reinmueller et al., 2018).

Interestingly, we observed smaller minimal TTCs when participants received visual warnings from the adaptive compared to the non-adaptive FCW even when drivers were not distracted. As both the adaptive and the non-adaptive FCW presented the same type of visual warning in undistracted situations, the observed higher criticalities for the adaptive FCW could be explained by the systems' differences in reliability. By occasionally experiencing incorrect warnings during adaptive FCW usage, drivers might have implicitly learned that there is a chance of receiving visuo-haptic support even in situations without distraction. As a consequence, drivers may have adopted a less conservative braking strategy for the adaptive FCW when being undistracted.

In addition to these effects of behavioral adaptation in the primary driving task, we also observed behavioral adaptation in the secondary tasks, although these effects were less robust. We found that drivers increased their engagement in the secondary task when they drove with the adaptive FCW relative to the non-adaptive FCW. This is in line with findings (Engström and Victor, 2009) and predictions that systems that specifically aim at mitigating the effects of distraction may have an unwanted impact on safety as users adapt their behavior, e.g., by allocating more attention to distracting tasks and stimuli (Donmez et al., 2003; Young and Regan, 2013).

Second, we found *compensation effects* of high-supportive warnings in distracted driving. When distracted drivers were supported by visuo-haptic warnings, they reacted faster and showed higher minimal TTCs in brake events. Crucially, by comparing expected visuo-haptic warnings in the adaptive FCW with expected visual warnings in the non-adaptive FCW, we made sure that these compensation effects were not confounded with expectancy. We further found that the positive effect of visuo-haptic support relative to visual support was restricted to distracted drivers, at least for the RTs. However, prior research has revealed that also undistracted drivers showed faster reactions to bimodal compared to unimodal support (e.g., Biondi et al., 2017; Ho et al., 2007; Levy, and Pashler, 2008; Politis et al., 2014) as well as to haptic compared to visual warnings (De Rosario et al., 2010; Scott and Gray, 2008). In our study, undistracted drivers benefitted to a similar extent as distracted drivers from unexpectedly presented visuo-haptic support only with respect to minimal TTCs as a measure of situational criticality. The present results may differ from those of previous studies as visuo-haptic warnings in our study were always unexpected in undistracted drivers. Thus, for undistracted drivers, compensation and expectancy was generally confounded. However, the unexpectedness of the haptic warning may have impaired RTs only by reducing the perceived need for immediate driver reaction, which was also suggested by Manser et al. (2004) who similarly found haptic warnings to lead to longer decision times while producing safer outcomes. The later braking onset could have been compensated by stronger decelerations as also observed by Naujoks et al. (2016), thus leaving situational criticality unimpaired. Indeed, haptic warnings have previously been reported to lead to stronger responses by more effectively communicating the required action (e.g., Navarro et al., 2010).

System *acceptance* is regarded crucial for the actual usage of a system and thus is particularly relevant for introducing adaptive ADAS into the market (Van der Laan et al., 1997). Adaptive ADAS should be associated with higher acceptance than standard, non-adaptive ADAS (Hajek et al., 2013; Smith et al., 2009) as they provide optimized support. We found that acceptance is still high if the adaptive system occasionally presents incorrect warnings. In the present study, even unreliable adaptive FCWs were rated to be more useful than non-adaptive FCWs with a higher intention to use. In line with the idea of presenting more helpful support to distracted drivers while presenting less urgent warnings to undistracted drivers (Smith et al., 2009), the warnings provided by the adaptive FCW in distraction situations were considered more helpful and more urgent than the warnings provided in situations without distraction. This implies that drivers obviously comprehended the concept of adaptive FCWs, which might be an important prerequisite for technology acceptance, and hence system usage (e.g., Najm et al., 2006). Interestingly, despite the occasionally provided incorrect support by the adaptive FCW, participants found the adaptive and non-adaptive FCW similarly trustworthy, satisfying and reliable. However, the adaptive FCW was rated to behave in a more underhanded manner than a non-adaptive FCW. Crucially, while adaptive FCWs were preferred by the majority of drivers, some argue in favor of non-adaptive FCWs due to reliability deficits of adaptive FCWs. Moreover, the haptic warnings provided by the adaptive FCWs in distraction situations were sometimes considered as too strong.

Regarding *warning effectiveness*, our findings suggest that the correctly adapted FCW was able to partially compensate the effects of driver distraction observed for the non-adaptive FCW. Correctly adapted warnings reduced RT deficits and fully offset criticality in brake events. However, two important issues must be considered: First, results have to be treated with caution as this analysis confounded expectancy and compensation effects. Second and crucially, there were no effectiveness benefits of the adaptive over the non-adaptive FCW regarding both driver responses and criticality measures. The compensatory effect of the adaptive FCW seems to have originated from both improvements in distracted drivers and impairments in undistracted drivers, resulting in comparable net effects in both FCW systems. This tendency for less prompt and less safe driving behavior in undistracted drivers could again reflect an implicit decrease in effort or attention due to the chance of being presented with visuo-haptic support by the unreliable adaptive FCW. The present study thus extends research on behavioral adjustments to system reliability for conventional, non-adaptive systems. As performance is generally related to the overall system reliability (for a review see Rein et al., 2013) and different forms of behavioral effects were identified for systems prone to false positives and systems prone to false negatives (e.g., Chancey et al., 2017; Dixon and Wickens, 2006) future studies on adaptive warning systems should investigate the exact effects of the presentation of false positive and false negative adaptive warnings. Only when the exact mechanisms behind unreliable adaptive warnings are revealed, adequate reliability levels can be defined for such systems.

Both expectancy and compensation effects were unaffected by *system design*. Regarding RTs and criticality measures the adaptive FCW using brake jerks and vibration warnings was able to better compensate for distraction than the non-adaptive FCW using mere visual warnings. These findings are supported by subjective data, which reveal a perceived safety benefit for the adaptive compared to non-adaptive FCW. However, we found no robust difference between brake jerks and vibrations in any of these measures. This evidence is contrary to the expectation that brake jerk warnings may lead to objectively safer driving than vibration warnings. The fact both forms of haptic support still required driver reactions could have counteracted safety differences. We suggest that in future studies the effect of system design on behavioral adaptation could be alternatively addressed by comparing a mere warning to a fully intervening function, such as the present FCWs to FCWs with autonomous braking.

Our present results have implications for the design of future adaptive warning systems. We could clearly demonstrate that unreliable adaptive support is associated with adverse effects whenever expectations are violated. Therefore, a first implication is that failures in driver state detection should be minimized. However, we cannot derive a recommendation regarding an optimal ratio of false positives and false negatives because both forms of failures in our study resulted in adverse effects. A second useful approach to reduce adverse effects associated with unreliable adaptive support is to minimize the perceptibility of adaptive adjustments of warnings. As predicted by Reinmueller et al. (2018), adjusting the timing of warnings should be less salient than adjusting warning modalities, and therefore, systems that adjust the timing of warnings according to driver distraction should be less likely to induce adverse effects.

4.1. Limitations

The present study has some limitations that should be addressed in future research on adaptive ADAS. First, to increase statistical power, the frequency of critical brake events was much higher than in real-world driving, as imminent crash warnings are assumed to occur approximately 15 times per year (Campbell et al., 2007). Accordingly, the suddenly triggered brake events were rather expected by drivers, which could have possibly led to unrealistic driving behavior (see Aust et al., 2013; Lee et al., 2002) and may have induced a more detailed mental model of the FCW system than one could expect during real-world driving. Thus, our findings may be more generalizable to frequently intervening ADAS such as adaptive Lane Departure Warnings. Second, we used an externally-paced RSVP task to generate a continuous source of distraction. However, even though drivers were instructed to complete the task as good as possible, we could not ensure that drivers were allocating their full attention to the secondary tasks at all times. This could have reduced the effects of distraction in our data because adaptive warnings were elicited according to the presence or absence of the task rather than the actual driver state (wizard-of-oz paradigm). To ensure a correct adaptation of system behavior, future research on adaptive ADAS should include the use of an online driver monitoring algorithm as proposed for workload monitoring by Hajek et al. (2013). Third, our manipulation of the strength of support in the adaptive FCW by using either steering-wheel vibration or brake jerk might have been too weak to affect behavioral adaptation. As proposed above, future studies should use more extreme manipulations, e.g., by contrasting a system that takes over full control in critical scenarios with mere warnings in which drivers are still responsible for the initiation of an adequate response.

4.2. Conclusion

The present results extend previous research on adaptive ADAS in several ways. Most importantly, we demonstrated adverse behavioral effects in situations in which an adaptive FCW fails to present the expected high support in distracted drivers. These adverse effects were due to two components, the absence of compensation and an expectancy effect indicative of behavioral adaption. However, while the adaptive FCW in our study facilitated driver reactions and decreased situational criticality in distracted relative to undistracted drivers, there were no effectiveness benefits of the adaptive over the non-adaptive FCW. We suggest that the absence of a general benefit of the adaptive FCW was due to the unreliability of the system. In sum, our results emphasize that driver reactions to failures and associated safety outcomes have to be taken into account when introducing dynamically adjusting functions in future ADAS.

Declarations of interest

This study was conducted as part of a research programme of the AUDI AG. Katharina Reinmueller is an employee of this company.

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