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Practice makes better – Learning effects of driving with a multi-stage collision warning

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ABSTRACT

Advanced driver assistance systems like (forward) collision warnings can increase traffic safety. As safety-critical situations (especially in urban traffic) can be diverse, integrated adaptive systems (such as multi-stage warnings) need to be developed and examined in a variety of use cases over time instead of the more common approach of testing only one-time effectiveness in the most relevant use case. Thus, this driving simulator experiment investigated a multi-stage collision warning in partially repetitive *trials* (T) of various safety-critical situations (*scenarios* confronting drivers with hazards in form of pedestrians, obstacles or preceding vehicles). Its output adapted according to the drivers' behavior in two warning stages (W1 – *warning* for moderate deceleration in less critical situations; W2 – *urgent warning* for strong, fast braking in more critical situations). To analyze how much drivers benefit from the assistance when allowed practice with it, the driving behavior and subjective ratings of 24 participants were measured over four trials. They comprised a *baseline* without assistance (T1) and three further trials with assistance – a *learning* phase repeating the scenarios from T1 twice (T2 + T3) and a concluding *transfer* drive with new scenarios (T4). As expected, the situation criticality in the *urgent warning* (W2) scenarios was rated higher than in the *warning* (W1) scenarios. While the brake reaction time differed more between the W1 scenarios, the applied brake force differed more between the W2 scenarios. However, the *scenario* factor often interacted with the *trial* factor. Since in later warning stages reaction time reductions become finite, the reaction strength gains importance. Overall the drivers benefited from the assistance. Both warning stages led to faster brake reactions (of similar strength) in all three assisted trials compared to the baseline, which additionally improved successively over time (T1–T3, T1 vs. T4, T2 vs. T4). Moreover, the drivers applied the gained knowledge from the learning phase to various new situations (transfer: faster brake reactions in T4 compared to T1 or T2). The well accepted and positively rated (helpful and understandable) two-stage collision warning can thus be recommended as it facilitates accident mitigation by earlier decelerations. Practice with advanced driver assistance systems (even in driving simulators) should be endorsed to maximize their benefits for traffic safety and accident prevention.

1. Introduction

During every day driving all kinds of more or less critical situations occur. While some go by without any consequences, others have severe consequences. According to the WHO (2015) worldwide around 1.25 million people die in road traffic accidents every year. However, safety-critical situations differ in all kinds of factors, like their location, the involved participants and their dynamics (speed, orientation, visibility) etc. In urban areas this diversity seems to reach its maximum compared to other road types as drivers are confronted with all kinds of traffic participants, from pedestrians, bicyclists to motorcyclists or other drivers, interacting at individual speeds in various arrays (e.g., intersections vs. straight roads). Therefore, urban areas pose an especially complex context for drivers and assistance systems, which have to collect and process all information promptly so that the driving behavior can always be adapted to the respective circumstances in time (Engel et al., 2013; Nöcker et al., 2000; Röglinger and Facchi, 2009). Even seemingly less critical situations may escalate if not handled properly by the drivers. Thus, each situation has its own requirements of how to be reacted to. As previous studies of Kazazi et al. (2016) and Winkler et al. (2018a) showed, drivers distinguish between situations in their subjective rating of the situation criticality and adapt their driving behavior accordingly. This in turn strongly influences the design of driver assistance systems like (forward) collision warnings (FCW). With decreasing distance to a safety-critical object a more urgent driver response might be necessary. So driver assistance systems should

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represent different urgencies by adapting their intrusiveness (Dingus et al., 1998; Najm et al., 1994).

This idea led to an integrated multi-stage warning approach which suggests a continuum of different urgency levels to always provide drivers with the support needed in the respective safety-critical situation (see Diederichs et al., 2010; Drüke et al., 2018; Jones and Hansman, 2007; Werneke et al., 2014; Winkler et al., 2016a; Winkler et al., 2018b). While only two warning stages were realized in the present experiment, more are imaginable. This might range from very early, merely informative to later, rather urgent reaction-requiring stages that activate the drivers increasingly (Campbell et al., 2007; Naujoks and Neukum, 2014; Zarife, 2014), or even to automatic vehicle interventions (General Motors Corporation & Delphi-Delco Electronic Systems, 2002). A driving simulator study of Winkler et al. (2018a) showed that driver reactions vary with different warning strategies (more or less urgent) and even when the alert is rather generic it is well understood. There, the different warning concepts were tested between groups of drivers. Each driver only experienced one type of warning throughout the entire drive. However, during real driving every driver might encounter different kinds of situations which require varied reactions. Thus, it is necessary to see if different warning stages experienced by one and the same driver are still as helpful as for different driver groups each experiencing only one stage of a warning.

A lot of research has shown positive effects of driver assistance (such as FCW) on the driving behavior in safety-critical situations resulting in improved traffic safety. Reduced collision frequencies and severities (prevented injuries) in assisted front-to-rear end scenarios were found in crash analyses (Cicchino, 2017) and driving simulator experiments (Lee et al., 2002). Amongst other assistance benefits earlier decelerations (Abe and Richardson, 2006; Bueno et al., 2014; Jamson et al., 2008; Popiv et al., 2010; Winkler et al., 2018a), more appropriate speeds and safety distances were reported (Ben-Yaacov et al., 2002; Lenné et al., 2008; Scott and Gray, 2008; van Driel et al., 2007). However, these studies typically used only one kind of warning strategy that requires one type of response in one specific scenario, like car-following (Abe and Richardson, 2006; Aust et al., 2013; Ben-Yaacov et al., 2002; Bueno et al., 2014; Jamson et al., 2008; Lee et al., 2002), lane keeping (Aksan et al., 2017), upcoming congestion (Naujoks and Totzke, 2014; Winkler et al., 2016a) or intersection scenarios (Werneke and Vollrath, 2013; Yan et al., 2015). For example, in the driving simulator study of Aust et al. (2013) drivers braked faster and at larger safety margins with a FCW compared to driving without assistance. However, the results were derived exclusively from one use case, a lead vehicle braking scenario. Similarly, Lubbe (2017) compared the benefits of different FCW designs in the aforementioned situation. Again, the system was effective, but would a FCW examined only in car-following situations be as effective in other situations? Could it be applied to further critical situations (e.g., involving other road users like crossing pedestrians or bicyclists and vice versa)? Above all, could such systems elicit different driver reactions like full braking in highly critical situations and mere speed reduction in less critical situations?

Besides single use case testing, most research demonstrates effectiveness of assistance systems only once. Repeated system exposure is examined less frequently. In studies attending to the topic, the subject of (adaptive or generic) collision warnings is underrepresented compared to for example (specific) lateral or longitudinal control systems like active cruise control (ACC) or lane keeping assistances (Aksan et al., 2017; Beggiato et al., 2015; Bianchi Piccinini et al., 2014; Janssen and Nilsson, 1993; Rudin-Brown and Parker, 2004). Of course, the relatively low occurrence of very critical situations requiring the activation of collision warnings (Parasuraman et al., 1997) might inhibit learning in everyday traffic. However, particularly in these rare cases drivers should be able to initiate fast, intuitive reactions just as if they were professionals who had years of system experience. Moreover, if drivers were allowed to gain experience with such systems, their effectiveness might even increase. Since multi-stage warnings (including rather early warning stages) could already warn drivers at a more advisory level like in less critical situations (Naujoks et al., 2015; Zarife, 2014), drivers might be confronted with the system more often. Therefore, possible long-term or learning effects of driving with collision warnings, especially in the form of multi-stage systems, have to be further investigated in various situations.

Some studies allowed their participants to gain system experience (e.g., Sayer et al., 2010; Várhelyi et al., 2015; Wilson et al., 2007). For example, in the Integrated Vehicle-Based Safety System (IVBSS) field test by Sayer et al. (2010) naturalistic driving data from vehicles equipped with a variety of warning systems (forward crash, longitudinal, lateral and curve-speed warnings) was recorded over the course of six weeks. Then the drivers' behavior during a baseline period of driving without assistance was compared to a final experimental period of driving with assistance. Mostly positive behavioral adaptations were found after this learning phase like fewer and shorter lane departures, increased turn signal use or shorter periods of critical time head-ways. Despite the permitted practice with the systems, this data evaluation resembled more a control vs. treatment comparison, which disregards incremental changes in the driving behavior. A more detailed analysis including a greater number of time stamps like in a study of successive test trials might illustrate possible learning effects over time better, but seems to be still lacking in the current research.

However, collision warning systems are harder to investigate this way, especially in a field setting which the named studies adopted. On the one hand, field studies offer the big advantage of a higher external validity compared to laboratory studies. On the other hand, they also pose challenges (Manser et al., 2013; Sullivan et al., 2016), in particular when the drivers' reaction to critical events is of interest. First of all, the critical events that trigger warnings and their number are difficult to be manipulated during the test phase. Secondly, the situational circumstances cannot be controlled. Since probably no situation resembles another, an analysis of incremental changes in the drivers' behavior might be difficult, as there are too many interfering variables inherent to the individual situation, like its location, the driven speed or the involved participants (and their own features). Additionally, to evaluate the human-machine-interaction (HMI) and actual assistance benefits without confounding factors like false alarms (disregarded in this study), the system has to perform perfectly. This however keeps challenging system manufacturers so far as the correct detection of safety-critical objects (like pedestrians or bicyclists) and prediction of their intentions is still work in progress (for further information see Cordts et al., 2017; Diederichs et al., 2018; Schmidt and Färber, 2009). Finally, field studies bear the risk of actual harm as a consequence of critical situations in real vehicles on the road as well.

Summing up, the effects of different warning stages have to be examined in various kinds of critical situations in order to estimate their effects on driving in real traffic, where this multitude of situations arises. Moreover, the learning experience with these warning systems needs investigation in order to gain ideas about how to introduce them to drivers. Thus, a driving simulator experiment was conducted in which drivers were exposed to a variety of safety-critical situations over four trials, using a two-stage collision warning system. In this study, the (incremental) influences of the *trials* and different safety-critical situations (*scenarios*) on the driving behavior (collision frequency, brake reaction time and brake maximum) were measured. Whereas the first two situations (one rather critical and one less critical), making up the first trial (T1), were unassisted as a baseline drive to measure the system effectiveness, all following three trials were assisted (T2–T4). While T2 and T3 repeated the situations from T1, the last trial (T4) consisted of two unknown situations to analyze whether the drivers learn how fast and strong to brake with the warning stages and can apply the gained knowledge from the learning phase (T2 + T3) to diverse new situations (transfer). In addition, subjective evaluations were conducted to check for system acceptance.

2. Method

2.1. Two-stage collision warning

For warning presentation a multicolor head-up display (HUD) measuring 15 × 15 cm (4° visual angle) was embedded in the virtual scenery and projected driver-centered on the front screen at 2.1 m distance to the driver. The aim of the warning system was to support drivers in avoiding collisions. Its design was based on the results of a previous study (Winkler et al., 2018a). As Table 1 illustrates, the two-stage collision warning comprised two rather generic warning stages. The first warning stage "*warning*" (W1), represented by a red warning triangle with an exclamation mark, was displayed when the ego vehicle (operated by the participant) reached a time-to-collision (TTC) between 8 s and 2 s to the hazardous object. It was meant to raise the attention of the drivers and prompt them to decelerate gradually by releasing the gas pedal or pressing the brake pedal slightly. If the deceleration was insufficient or the hazardous objects appeared at a TTC below 2 s, an "*urgent warning*" (second warning stage; W2) was triggered. Then the drivers were supposed to show fast and strong reactions. While the *warning* was solely visual, the stop symbol presentation in the *urgent warning* was accompanied by an acoustic signal in order to increase its salience and urgency. Both warning stages remained activated as long as the above mentioned TTC criteria were met.

The TTC thresholds were selected based on the combined results of expert ratings and diverse studies on the timing of advanced driver assistances (e.g., LeBlanc et al., 2001; Lee et al., 2002; Naujoks, 2015; Spence and Ho, 2008; Schmidt et al., 2009; Werneke et al., 2014; Winkler et al., 2016a; Winner et al., 2009). For the different safety-critical situations, it was examined at which TTCs experts were comfortable with a *warning* (leaving enough time to reduce speed gradually) and still had sufficient time to elicit a brake reaction and come to a safe standstill with an *urgent warning*. So they were able to perceive and react to each warning stage separately (as W2 might override W1 if presented too closely). By these expert pilot tests it was ensured that the TTCs selected were appropriate in this manner.

Table 1
The visual and acoustic signals of the two-stage collision warning and their timing.

Warning stage	*Warning* (W1)	*Urgent warning* (W2)
Visual in HUD		
Acoustic	–	1 kHz ("Beep")
TTC threshold	2 s ≤ × < 8 s	× < 2 s

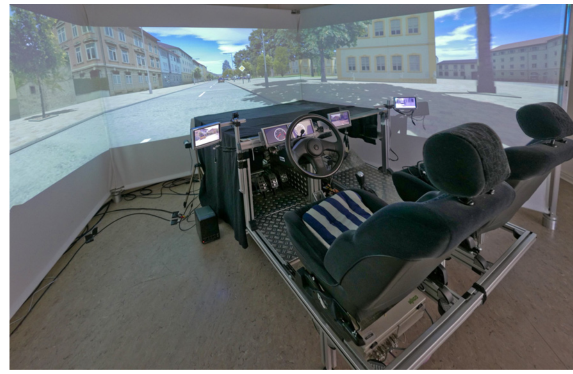


Fig. 1. Picture of the static medium fidelity driving simulator.

2.2. Driving simulation

The experiment was conducted in a static medium fidelity driving simulator of the Technische Universität Braunschweig (see Fig. 1). A seat box surrounded by three screens (ahead: 1.85 m × 2.10 m, left and right: 1.85 m × 2.20 m) at about 2.1 m distance to the driver form this driving simulator. It is equipped with accelerator and brake pedals, two car seats as well as a steering wheel with force feedback. Three LCD screens served as rear-view mirrors. The virtual driving scenery, created by the driving simulation software SILAB 4.0 (from WIVW, Krüger et al., 2005; see www.wivw.de), is projected with full HD resolution (1920x1080 px) by three beamers providing a 180° degree field of view. Thus, the simulator gives drivers a rather realistic feeling of driving in a real car, which is additionally enhanced by an acoustic simulation of traffic sounds like wind and engine noises.

The test drive took place in a simulated urban area with a speed limit of 50 km/h. As road type, mainly single-lane roads were used. The test track consisted of straight parts, elongated curves and a few intersections (mostly unregulated), at which the drivers usually went straight in order to keep the risk of simulation sickness low. It resembled a small city by daylight with fluent traffic (no jams), some parking cars and plantation at the side, pedestrians walking around and bus stops being attended to. Random traffic (like oncoming or lead vehicles as well as vehicles approaching from behind) was simulated over the whole course of the test track. Besides, scenes alike the critical scenarios were implemented to make the safety-critical situations less predictable. Drivers were navigated by arrows in the instrument panel near the speedometer and an additional voice output. All eight safety-critical situations (*scenarios*) of the previous study (Winkler et al., 2018a), with diverse hazardous objects (pedestrian, bicyclist, lead vehicle or obstacle) at various locations (intersection, straight road, curve or hill), were reused. Yet, only four of them are analyzed in this paper (see Table 2, for other scenario results see Winkler et al., 2016b).

Table 2
Textual and pictorial depiction of the four safety-critical situations analyzed in this paper with the encountered object type and its location.

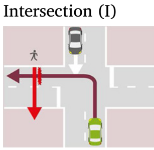
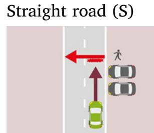
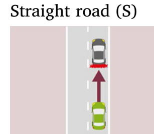
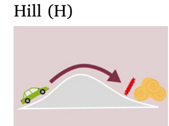
Object	Pedestrian (P)		Lead vehicle (L)	Obstacle (O)
Location **Picture**	Intersection (I) 	Straight road (S) 	Straight road (S) 	Hill (H) 
Description	When turning left at an uncontrolled intersection with oncoming traffic (having the right of way), a pedestrian, emerging from a visible crowd at the farther end, crosses the ego vehicle's turning path (accelerating to 4 m/s)	While driving straight ahead on a one-way road a pedestrian hidden behind parking vehicles crosses the ego vehicle's path from right to left (green area) with 2 m/s (*evasive maneuver possible*)	On a straight road without oncoming traffic, a lead vehicle suddenly brakes (decelerating with 25 m/s^2 to 3 m/s) without any warning or reason (*evasive maneuver possible*)	When driving straight ahead with oncoming traffic, a hay bale blocking the ego vehicle's path suddenly becomes visible after being hidden from drivers' sight by a hill

Fig. 2. Pictures of the *warning* (W1) scenarios (OH, left and LS, right) from drivers' perspective in the driving simulator.

Fig. 3. Pictures of the *urgent warning* (W2) scenarios (PI, left and PS, right) from drivers' perspective in the driving simulator.

Table 3
Order of how the driver groups A and B encountered the four regarded *scenarios* (OH, LS, PI and PS) over the four *trials* (T1–T4) with the warning stage triggered first (W1 or W2).

		Assistance	Without	With		
		Phase	Baseline	Learning		Transfer
	Scenario	**Trial**	T1	T2	T3	T4
A	*Warning* (W1)		LS	LS	LS	OH
	Urgent warning (W2)		PI	PI	PI	PS
B	*Warning* (W1)		OH	OH	OH	LS
	Urgent warning (W2)		PS	PS	PS	PI

These safety-critical situations were designed in a way to create a need of warnings. The situations in scenario PI and PS had proved to be of higher criticality than in the scenarios LS and OH (according to subjective ratings in Winkler et al., 2018a). This and the low TTC values when a hazard was encountered in them made a direct *urgent warning* (W2) necessary, while an earlier *warning* (W1) sufficed in LS and OH (see Figs. 2 and 3). Nevertheless, depending on the behavior of the drivers the situations could become more or less critical. Drivers naturally differ in matters like following distances, speed keeping or turning behavior. This random within-subjects variation therefore has to be regarded when interpreting the results.

very low			rather low			moderate			rather high			very high		
-	0	+	-	0	+	-	0	+	-	0	+	-	0	+

Fig. 4. Two-stage rating scale by Heller (1982) to measure the *situation criticality* of each scenario set, and the *understandability*, *helpfulness* and *distraction* of each warning stage.

2.3. Experimental design

The test drive was structured into four *trials* for every participant (see Table 3), beginning with two *scenarios* (one for each warning stage)

Table 4
Dependent measures analyzed in this paper.

Objective variables		
Measure	**Unit**	**Description**
Collision frequency	%	Number of times the ego vehicle crashed into the safety-critical object on encounter
Brake reaction time	s	Time from assistance onset (notional in baseline) until the brake pedal is pressed (≥0.2 s, including participants who collided with the safety-critical object)
Brake maximum	%	Maximum pressing of the brake pedal after assistance onset until the speed is zero or the brake pedal is released again (in percent of the sample maximum)
Subjective variables		
Warning rating		**Item** [1 (*very low*, −) … 15 (*very high*, +); Heller, 1982]
Situation criticality		"How critical were the experienced situations with the *warning/urgent warning*?"
Understandability		"How understandable was the *warning/urgent warning* in the experienced situations?"
Helpfulness		"How helpful was the *warning/urgent warning* in the experienced situations?"
Distraction		"How distracting were the *warning/urgent warning* in the experienced situations?"
System acceptance		**Item** [−2 (negative pole) … +2 (positive pole); Van der Laan et al., 1997]
Usefulness		1) useful, 3) good, 5) effective, 7) assisting, 9) raising alertness
Satisfaction		2) pleasant, 4) nice, 6) likeable, 8) desirable

in the first trial T1 without assistance as baseline in order to test its effectiveness. Then a learning phase with assistance followed, comprising two trials (T2 and T3) with a repetition of six scenarios in randomized order. These trials were used to examine how the gained experience with the warning system might change its effects on the drivers' behavior. Both trials contained the two scenarios from T1 in addition to four more different scenarios, which are not focused in this paper (for further information see Winkler et al., 2016b). Finally, the drivers encountered two new scenarios (one with *warning* and one with *urgent warning*) in trial T4 (transfer). This allowed examining how well the gained experience with the assistance system could be transferred to new situations. As Table 3 shows, there were two groups (A and B) of twelve drivers each. Each group experienced an individual pair of scenarios repetitively from trial T1 until T3 (within-subjects variation), whereas for the final trial T4 those pairs were switched between both groups. Thus, the scenarios in T4 were experienced only once in each group, as they were part of the baseline (T1) and learning phase (T2, T3) of the other group (no full-factorial design).

The driving behavior (e.g., position, speed, pedal and steering wheel activity) was logged at a frequency of 60 Hz by the simulation software. In order to examine the driver reactions to the two-stage collision warning system, the number of collisions and the brake reaction time and force (brake maximum) were investigated as objective variables (see Table 4). Additionally, subjective ratings by the drivers were collected and a qualitative interview was conducted at the end of the experimental session. Table 4 describes all measured variables.

The subjective evaluation measuring the acceptance of the two-stage warning system by the drivers included two different scales. On the one hand, a system acceptance questionnaire (from Van der Laan et al., 1997) was given before and after experiencing the system to see whether the expectations of the warning system were met (regarding its usefulness and satisfaction). On the other hand, a 15-point rating scale (see Fig. 4; Heller, 1982) investigated the criticality of situations experienced within the sets of scenarios designed for a *warning* (W1) or an *urgent warning* (W2) as manipulation check and the understandability, helpfulness and distraction of each warning stage. In this two-stage rating the drivers first had to choose one out of five labeled categories before refining their rating by selecting one out of three subcategories (-, 0, +). This rating was then transformed into numbers from 1 to 15 ("*very low*" to "*very high*").

2.4. Participants

In sum twenty-four drivers with an average age of 26.8 years (SD = 8.2 years) participated in this driving simulator experiment (13 female, 11 male). Out of the thirty-one drivers recruited through flyers, mailing lists and advertisements, seven had to be excluded due to effects of simulation sickness in the prior training drive obligatory for participation. The participants had on average 9.2 years (SD = 8.5 years) of driving experience. They mainly drove less than 3000 km per year as the majority were university students without a car of their own. All participants had normal or corrected-to-normal visual acuity. They were compensated with 10 € for a successful participation or received course credits (if psychology students).

2.5. Procedure

After the participants had been welcomed, they received a written instruction preparing them for the training drive and explaining the objectives of the experiment (investigation of driving behavior and subjective evaluation of a hazard warning for complex urban situations). They provided informed consent by signature and filled in a demographic questionnaire. When participants were familiarized with the simulator and showed no signs of simulation sickness during the 15 min training drive, they experienced the first two safety-critical situations unassisted as a baseline (T1). Then drivers were instructed

Table 5
Number of data points per *trial* and *scenario* included (*valid*) and excluded from the brake reaction examination (due to no apparent brake reaction to the warnings (*none*) or a brake reaction time of > *3.2 s* or < *0.2 s*).

Warning stage	*Warning* (W1)		*Urgent warning* (W2)		
Scenario	OH	LS	PI	PS	Overall
valid	41	47	37	47	172 (89.6%)
none	3	1	0	1	5 (2.6%)
> 3.2 s	3	0	0	0	3 (1.6%)
< 0.2 s	1	0	11	0	12 (6.3%)

about the two-stage warning system and evaluated it based on their expectations ('before' system acceptance). The following test drive comprised three more trials with assistance (T2–T4) and took about 15 min. Afterwards drivers filled out two questionnaires ('after' system acceptance and another subjective rating of the warning system). The experiment concluded with an interview to investigate the warning concepts in more detail (e.g., regarding its actual understanding, timing and helpfulness). Finally, the drivers were thanked and compensated for their participation. The entire experiment lasted about an hour.

2.6. Data analysis

The data analysis was conducted with IBM SPSS Statistics 23. In order to investigate the brake reaction, the time from warning onset until the drivers pressed the brake pedal (brake reaction time) was employed. In some occasions, when drivers received the *warning* (W1), decelerating only by releasing the gas pedal without pressing the brake pedal was a sufficient reaction. As Table 5 shows, about 4% of all hazard encounters (primarily of scenario OH) were not included in the data analysis due to drivers showing a very late brake reaction or none (brake reaction time cutoff value of 3.2 s at a g-level of 3.0). In another 6% of all encounters the drivers reacted before warning onset or in less than 0.2 s, which was assumed to be the minimum time to brake upon warning presentation. This case occurred particularly often in the first trial T1 in scenario PI (see Table 5). After excluding these cases, overall 90% of all data points were left for the statistical analysis. The number of participants included per group is therefore always given at the bottom of a chart and has to be born in mind when interpreting the results of the brake reaction time and brake maximum. In every encounter of scenario OH only the first warning stage was needed, while in about 19% of the LS scenarios the second warning stage followed. In these cases the *warning* (W1) was displayed for merely a second before the *urgent warning* (W2) and drivers braked within about 0.4 s (± 0.2 s).

Before the actual analysis, it was checked whether the *scenarios* really differed from each other as intended, in order to prompt different warning stages. To this aim, the subjective ratings of the situation criticality between both sets of scenarios were compared in a Wilcoxon signed-rank text (both W1 scenarios intended for triggering a *warning* (LS, OH) and the W2 scenarios for a direct *urgent warning* (PI, PS)). Due to an absence of collisions in the scenarios intended for W1 in each of the four trials, the parameter collision frequency is only evaluated in the two scenarios intended for W2. However, this also indicates that the W1 scenarios were indeed less critical than the W2 scenarios. In order to see whether the drivers learned to react faster in the same situations over time and whether this differed with the *scenario*, the collision frequency (chi-squared (X^2) test), the brake reaction time and the brake maximum (mixed design ANOVAs including the within-subjects factor *trial* (3) and the between-subjects factor *scenario* (2)) were analyzed separately for the W1 and the W2 scenarios over the trials T1 (without assistance), T2 and T3 (with assistance).

The data were further analyzed for an assistance effect regarding whether drivers actually benefited from driving with assistance.

Therefore, trial T1 without assistance was compared to T4 with assistance (but completely new scenarios) for both kinds of scenarios (W1 and W2). Four 2 × 2 ANOVAs with the between-subjects factors *trial* and *scenario* were conducted for the brake reaction time and the brake maximum. Another chi-squared (X^2) test compared the collision frequency in T1 and T4 for the scenarios with direct *urgent warning* (W2). Furthermore, the assisted trials T2 (with known scenarios) and T4 (with completely new scenarios) were analyzed in both kinds of scenarios (W1 and W2) in order to check for transfer effects onto new situations from driving with assistance. Again four 2 × 2 ANOVAs including the two between-subjects factors *trial* and *scenario* investigated the brake reaction time and the brake maximum, while a chi-squared (X^2) test compared the collision frequency in T2 and T4 for the scenarios with direct *urgent warning*. Finally, a Wilcoxon signed-rank test compared the subjective ratings of the *warning* (W1) to the *urgent warning* (W2) regarding their understandability, helpfulness and distraction. Another Wilcoxon signed-rank test analyzed whether the system acceptance changed from prior to after the test drive.

If sphericity was violated, the Greenhouse-Geisser corrected degrees of freedom were used. A significance level of $p \leq .05$ was adopted for all statistical tests, unless multiple testing made Bonferroni corrections necessary (as in all brake reaction time and brake maximum analyses). Table 6 summarizes all results derived from the ANOVAs of the brake reaction time and brake maximum. For the ANOVA and the nonparametric Wilcoxon signed-rank test, η^2 or r respectively, are given as a measure of the effect size. All presented means are given with 95% confidence intervals (CI) as margins of error.

3. Results

3.1. Manipulation check

The situation criticality rated subjectively after all four trials differed significantly between the two scenario sets intended for W1 (LS, OH) and W2 (PS, PI; $z = -4.30$, $p < .001$, $r = -0.88$). While the encounters in the W1 scenarios were together rated *moderate* ($M = 7 \pm 0.9$) on the criticality scale, the W2 scenarios reached a much higher rating, being *very high* ($M = 14 \pm 0.5$). Thus, regarding the subjective situation criticality, the scenario sets differed as intended.

3.2. Learning effect (trials T1 to T3)

The collision frequency over the first trial without assistance (T1) and the following two trials with assistance (T2 and T3) did not differ significantly between the trials in either of the two W2 scenarios (PS: $X^2 = 0.67$, $p = .717$; PI: $X^2 = 3.25$, $p = .197$). However, the absolute number of collisions decreased gradually with trial repetitions (T1–T3), for scenario PS (pedestrian crossing at straight road) from 58%, 50% to 42% and scenario PI (pedestrian crossing at intersection) from 25%, 17% to 0%. In the W1 scenarios no collisions occurred in any trial.

All results of the analyses of the brake reaction time and the brake maximum over the first trial without assistance (T1) and the following two trials with assistance (T2 and T3) are reported in Table 6. The analysis of the brake reaction time showed a significant interaction effect of the within-subjects factor *trial* and the between-subjects factor *scenario* in the scenarios intended for a *warning* (W1) as well as in the scenarios intended for a direct *urgent warning* (W2). Furthermore, for both scenario types (W1 and W2), there was a significant main effect of the within-subjects factor *trial* and the between-subjects factor *scenario*. As can be seen in Fig. 5 (left) for the W1 scenarios and Fig. 5 (right) for the W2 scenarios, the brake reaction time differed between the *scenarios* assigned for triggering the same warning stage, with faster brake reactions in scenario LS (lead vehicle stopping at straight road) compared to OH (obstacle behind hill) and in scenario PS compared to PI, respectively. Despite this scenario difference being more distinct in the W1 scenarios than in the W2 scenarios, it diminished over the *trials* for both scenario types (decreasing about 70% from T1 to T3 in W1 scenarios and 80% in W2 scenarios).

Independent of the assigned warning stage, the drivers showed a decreasing brake reaction time with an increasing number of trial repetitions in all scenarios. Post-hoc tests for the within-subjects factor *trial* also showed significant differences in every trial comparison for each scenario type (W1: T1–T2: $p = .001$, T1–T3: $p < .001$, T2–T3: $p = .013$; W2: T1–T2: $p = .001$, T1–T3: $p < .001$, T2–T3: $p < .001$). For example, in the scenarios OH (W1) and PI (W2) the brake reaction time reduced by half from T1 to T3 (see Fig. 5, left and right). However, the brake reaction time improved less in the scenarios, in which the drivers' initial brake reaction was already quite fast (around one second) like in the scenarios LS (W1) and PS (W2, see Fig. 5, left and right). The slowest brake reaction for all scenarios was reached in T1 without assistance, whereas the fastest brake reaction was found in T3 with assistance and most experience. Regarding both trials with assistance (T2 and T3), the brake reactions with the *urgent warning* (see Fig. 5 right) were faster than with the *warning* (see Fig. 5, left).

The analysis of the brake maximum over the first three trials (T1–T3) showed a significant main effect of the between-subjects factor *scenario* for the W2 scenarios. However, no further significant effects were found for the *warning* (W1) or *urgent warning* (W2) scenarios, only tendencies towards significance for an interaction effect of the within-subjects factor *trial* and the between-subjects factor *scenario* and for a main effect of the factor *trial*. Descriptively, independent of the trials the drivers reached clearly higher brake maxima in the W2 ($M = 85\% \pm 6\%$, $n = 61$) compared to the W1 scenarios ($M = 34\% \pm 6\%$, $n = 65$). While the maximal applied brake force in both W1 scenarios was quite similar, the drivers showed a 24% stronger

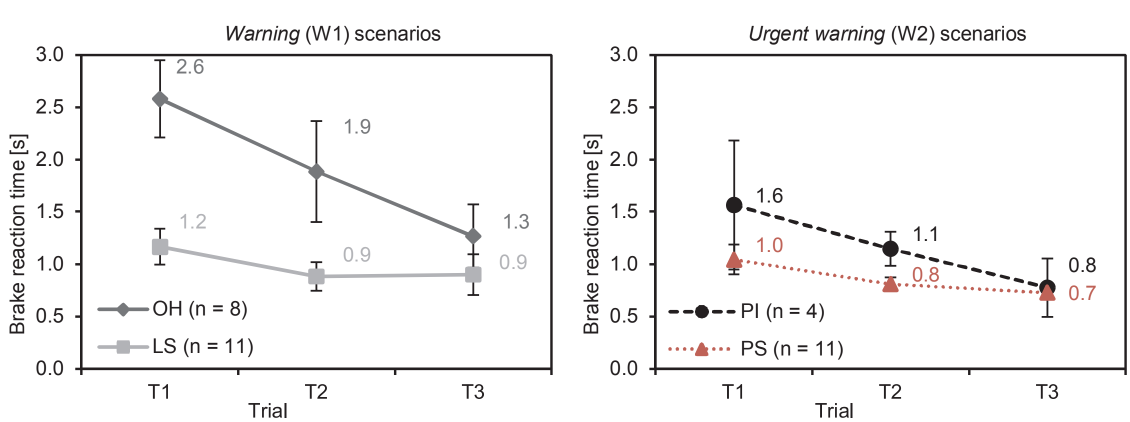


Fig. 5. Mean brake reaction time per *trial* (T1 to T3) and *scenario* in the scenarios intended for the first warning stage (W1, left) and the second warning stage (W2, right), with 95% CI and number of participants (n).

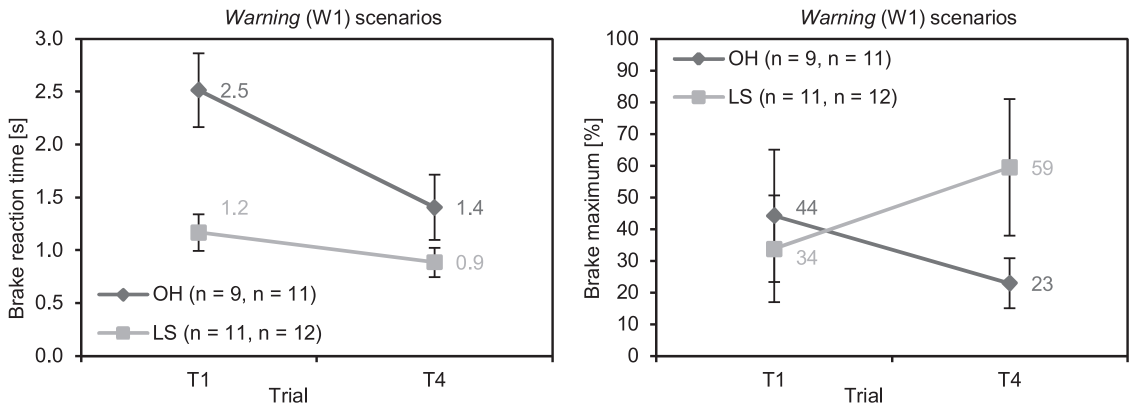


Fig. 6. Mean brake reaction time (left) and brake maximum (right) per *trial* (T1 and T4) and *scenario* in the scenarios intended for the first warning stage (W1), with 95% CI and number of participants (n).

brake reaction in scenario PS than in PI, both of them being W2 scenarios (PS: $M = 95\% \pm 5\%$, $n = 35$; PI: $M = 71\% \pm 11\%$, $n = 26$).

3.3. Assistance effect (trials T1 and T4)

The collision frequency did not differ significantly between the drivers who experienced the regarded scenario in the first trial without assistance (T1) and those who experienced it for the first time in the fourth trial with assistance (T4) in either of the two W2 scenarios (PS: $X^2 = 0.17$, $p = .682$; PI: $X^2 = 0.25$, $p = .615$). However, the absolute number of collisions was lower in the last trial compared to the first, for scenario PS (pedestrian crossing at straight road) 50% and 58%, and for scenario PI (pedestrian crossing at intersection) 17% and 25%, respectively.

All results of the analyses of the brake reaction time and the brake maximum for trial T1 without assistance and T4 with assistance are reported in Table 6. The analysis of the brake reaction time in the scenarios intended for a *warning* (W1) showed a significant interaction effect of the between-subjects factors *trial* and *scenario* as well as two separate significant main effects for each of the factors. In the scenarios intended for a direct *urgent warning* (W2), there was a significant main effect of the between-subjects factor *trial* on the brake reaction time. However, merely tendencies towards significance were found for a main effect of the between-subjects factor *scenario* and an interaction effect of the between-subjects factors *trial* and *scenario*.

As can be seen in Fig. 6 (left), in the scenarios with a *warning* (W1) the drivers showed faster brake reactions in trial T4 with assistance than in trial T1 without assistance. However, this *trial* difference was 0.8 s greater in scenario OH (obstacle behind hill) compared to scenario LS (lead vehicle stopping at straight road), as the initial brake reaction time in the baseline (T1) was also much higher in scenario OH. Independent of this *trial* effect, the drivers showed different levels of brake reaction time in both W1 scenarios, (see Fig. 6, left). On the contrary, the brake reaction time level in the two scenarios intended for a direct *urgent warning* (W2) was rather similar. The brake reaction time in the W2 scenarios decreased about 0.4 s from an average of 1.2 s ($\pm$ 0.2 s, $n = 17$) to 0.8 s ($\pm$ 0.1 s, $n = 23$), which is a 0.1 s stronger decrease than for scenario LS, but less than in OH (both intended for W1).

The comparison of the brake maximum for trial T1 without assistance and T4 with assistance in the scenarios intended for a *warning* (W1) showed a significant interaction effect of the between-subjects factors *trial* and *scenario*, but no further significant main effect for either factor. In the scenarios intended for a direct *urgent warning* (W2), there was a significant main effect of the between-subjects factor *scenario* on the brake maximum. Neither a main effect of the between-subjects factor *trial* nor an interaction effect of the between-subjects factors *trial* and *scenario* became significant.

As can be seen in Fig. 6 (right), in the scenarios designed for a *warning* (W1) the brake maximum differed significantly between both W1 *scenarios* over the *trials*. While in scenario LS the brake maximum increased from the first trial without assistance to the last trial with assistance, it was inverse in scenario OH. However, the average level of maximal applied brake force within scenario LS in T4 was still 15% higher than within scenario OH in T1, leading to an even greater difference between both W1 scenarios in T4 (see Fig. 6, right). The significant *scenario* difference within the W2 scenarios, showed again that the drivers initiated clearly stronger brake reactions in scenario PS ($M = 93\% \pm 6\%$, $n = 23$) than in scenario PI ($M = 75\% \pm 13\%$, $n = 17$).

3.4. Transfer effect (trials T2 and T4)

Since in each of the two W2 scenarios the same amount of collisions occurred in the second (T2) and fourth trial (T4), no statistical test was conducted (PS with a pedestrian crossing at a straight road: 50%; PI with a pedestrian crossing at an intersection: 17%). Further analyses compared the brake reaction time and brake maximum in the two scenarios either designed for a *warning* (W1) or a direct *urgent warning* (W2) between T2 (familiar scenarios, unfamiliar assistance) and T4 (unfamiliar scenarios, familiar assistance). The according results are summarized in Table 6. Regarding the brake reaction time in the W1 scenarios, a significant main effect for each between-subjects factor *trial* and *scenario* was found. An interaction effect of both factors became only marginally significant. However, in the W2 scenarios there was neither a significant interaction nor any significant main effect of either between-subjects factor on the brake reaction time.

Fig. 7 (left) shows that in both scenarios with a *warning* (W1) the drivers initiated an earlier brake reaction in T4 than in T2 even though the situations were not familiar to them as they were in T2. However, the brake reaction time decrease was somewhat more drastic in scenario LS (lead vehicle stopping at straight road) than in scenario OH (obstacle behind hill), in which the drivers generally showed a distinctly lower level of brake reaction time. On the contrary, the brake reaction time with the *urgent warning* (W2) was on a similarly low level ($M = 0.9\,s \pm 0.1\,s$, $n = 46$) in both W2 scenarios (PS and PI) and trials (T2 and T4).

The comparison of the brake maximum in trial T2 and T4, showed a significant main effect of the between-subjects factor *scenario* in both scenario types (W1 and W2). There were no further significant effects in the *warning* (W1) or *urgent warning* (W2) scenarios, neither a significant main effect of the between-subjects factor *trial* nor an interaction effect between both factors. Descriptively, the level of brake maximum in the rather critical scenarios with an *urgent warning* was clearly higher than in the less critical scenarios with a *warning*. Regarding the *scenario* effect within the W2 scenarios, in scenario PI only about three quarters of

Table 6
ANOVA results for the learning effects (T1 to T3), assistance effects (T1 and T4) and transfer effects (T2 and T4) of the factors *trial* and *scenario* on the brake reaction time and brake maximum.

		Brake reaction time								Brake maximum							
	Scenario	*Warning* (W1)				*Urgent warning* (W2)				*Warning* (W1)				*Urgent warning* (W2)			
	Effect	*F*	*df*	*p*	n^2	*F*	*df*	*p*	n^2	*F*	*df*	*p*	n^2	*F*	*df*	*p*	n^2
T1 to T3	*Trial*	33.9	2,34	**<.0001**	0.67	31.6	1.2,15.5	**<.0001**	0.71	0.6	2,34	.529	0.04	3.6	1.3,16.5	.067	0.22
	Scenario	56.8	1,17	**<.0001**	0.77	25.9	1.0,13.0	**<.0001**	0.67	1.5	1,17	.235	0.08	8.7	1.0,13.0	**.011**	0.40
	Trial x Scenario	14.7	2,34	**<.0001**	0.46	5.8	1.2,15.5	**.024**	0.31	3.0	2,34	.065	0.15	3.4	1.3,16.5	.076	0.21
T1 and T4	*Trial*	40.4	1,39	**<.0001**	0.51	20.0	1,36	**<.0001**	0.36	0.1	1,39	.787	0.00	0.2	1,36	.671	0.01
	Scenario	72.7	1,39	**<.0001**	0.65	3.1	1,36	.088	0.08	2.7	1,39	.108	0.06	6.3	1,36	**.017**	0.15
	Trial x Scenario	14.4	1,39	**.001**	0.27	3.4	1,36	.072	0.09	8.7	1,39	**.005**	0.18	0.0	1,36	.825	0.00
T2 and T4	*Trial*	5.5	1,42	**.023**	0.12	2.5	1,42	.121	0.06	2.6	1,42	.114	0.06	0.3	1,42	.608	0.01
	Scenario	41.8	1,42	**<.0001**	0.50	2.4	1,42	.129	0.05	15.3	1,42	**<.0001**	0.27	15.0	1,42	**<.0001**	0.26
	Trial x Scenario	4.3	1,42	.044	0.09	2.7	1,42	.110	0.06	1.7	1,42	.197	0.04	0.5	1,42	.466	0.01

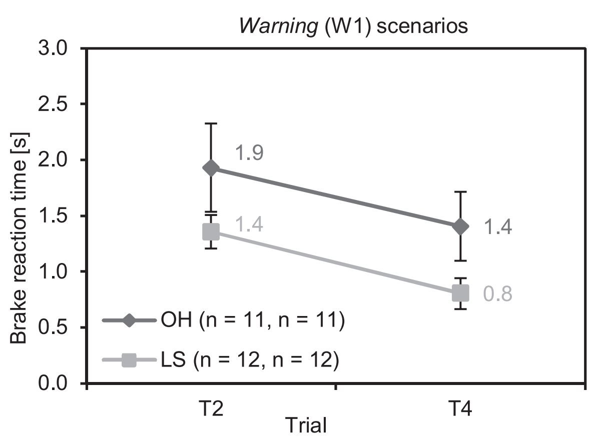


Fig. 7. Mean brake reaction time per *trial* (T2 and T4) and *scenario* in the scenarios intended for the first warning stage (W1), with 95% CI and number of participants (*n*).

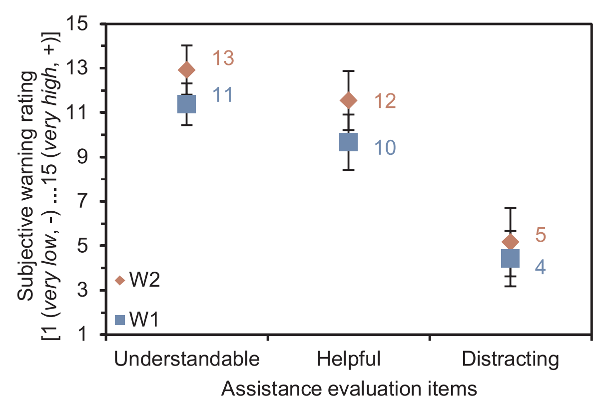


Fig. 8. Mean subjective ratings of the understandability, helpfulness and distraction of the two-stage warning system per warning stage (W1 and W2), with 95% CI.

the brake maximum in scenario PS were reached (PI: $M = 72\% \pm 13\%$, $n = 22$; PS: $M = 96\% \pm 3\%$, $n = 24$). Within the W1 scenarios, the average value of applied maximum brake force in scenario LS was about twice as much as in OH (LS: $M = 49\% \pm 14\%$, $n = 24$; OH: $M = 22\% \pm 5\%$, $n = 22$).

3.5. Subjective ratings of the warning system / system acceptance

In general, the drivers rated the two-stage warning system *rather high* to *very high* in its understandability and helpfulness, yet *rather low* in its distraction potential (see Fig. 8). However, the Wilcoxon signed-rank test showed that the *urgent warning* (W2) was significantly more understandable and helpful than the *warning* (W1; understandability: $z = -2.71$, $p = .007$, $r = -0.55$; helpfulness: $z = -2.16$, $p = .031$, $r = -0.44$). As can been seen in Fig. 8, this amounts to a difference of about two scale points for both items (understandability: W1 *rather high* ($M = 11$) and W2 *very high* ($M = 13$); helpfulness: W1 *rather high* ($M = 10$) and W2 *rather high* ($M = 12$)). The distraction potential of both warning stages though did not differ significantly ($z = -1.12$, $p = .264$). Both stages were rated *rather low* on this scale (W1: $M = 4$ and W2: $M = 5$, see Fig. 8).

The overall system acceptance judgement was also positive on a scale from -2 to $+2$ (Van der Laan et al., 1997). There was no significant difference in the subjectively rated system usefulness or satisfaction between the drivers' judgement before and after experiencing the warning system in the test drive (usefulness: $z = -0.18$, $p = .861$; satisfaction: $z = -0.08$, $p = .935$). The two-stage warning system was on average rated rather useful ($M = +1.1$) and satisfying ($M = +0.7$).

4. Discussion

This driving simulator experiment investigated the effects of a multi-stage collision warning (with two implemented warning stages: *W1 – warning, W2 – urgent warning*) on the number of collisions, brake reaction time and brake maximum of twenty-four drivers in different *scenarios* (safety-critical situations with pedestrians, obstacles or preceding vehicles as hazards) over four *trials* (T). Subjective ratings of the warning system and the situation criticality were measured additionally. After a baseline (T1) without assistance, the drivers were allowed practice with the assistance in a learning phase which repeated the same set of two scenarios (one less and one more critical) from T1 twice (T2 + T3). The last trial (T4) comprised two completely unknown scenarios in order to examine transfer effects.

As intended, the *warning* (W1) scenarios were subjectively rated of a lower situation criticality than the *urgent warning* (W2) scenarios. This is quite in line with the driving behavior over all trials. Independent of the trials, the overall fastest and strongest brake reactions were reached in the W2 scenario PS with a pedestrian crossing at a straight road (brake reaction time: $M = 0.8\,s \pm 0.05\,s$; brake maximum: $M = 95\% \pm 4\%$). It was the most critical scenario with about half the drivers having a collision. Slightly slower brake reactions of about a quarter less force were found in the other W2 scenario PI with a pedestrian crossing at an intersection (brake reaction time: $M = 1.0\,s \pm 0.17\,s$; brake maximum: $M = 73\% \pm 9\%$). Thus, scenario PI was somewhat less critical than PS, which might be due to the speed at *urgent warning* activation. As in scenario PI the drivers turned left at an intersection when the critical event was encountered, they were much slower than in scenario PS, in which they were driving straight ahead like in the other two W1 scenarios (average speed over all trials in PI: 18 km/h ± 6 km/h and PS: 49 km/h ± 3 km/h). Therefore, collisions in scenario PI (amounting to about 15%) might have been also less likely than in scenario PS and the brake reaction could be somewhat more relaxed, however still stronger than in the W1 scenarios.

No collisions in any of the trials occurred in the W1 scenarios. In scenario LS (lead vehicle stopping at straight road) drivers showed a similar brake reaction as in scenario PI regarding its timing ($M = 1.0\,s \pm 0.08\,s$). However, the strength of this brake reaction was a lot less since the scenario was less critical ($M = 43\% \pm 9\%$). Even less and hence the least amount of brake force was combined with the slowest brake reaction time when an obstacle blocked the road behind a hill in the other W1 scenario OH (brake reaction time: $M = 1.8\,s \pm 0.20\,s$; brake maximum: $M = 27\% \pm 6\%$). To sum up, the scenario sets clearly differed in their situation criticality (reflected in the TTC thresholds triggering each warning stage) to which the drivers adapted their driving behavior regarding their reaction time and strength.

Overall, the results show that with the two-stage warning system the drivers are able to handle less critical situations without them becoming more critical and also avoid more severe crashes in rather critical situations due to earlier deceleration and brake force adaptation. On the one hand, this indicates that the two-stage warning system is well understood by the drivers as they react differently to the two warning stages. On the other hand, the difference in driver reactions between the scenario types also shows that drivers adapt their reactions to the situation itself. Thus, the warning system seems to assist drivers in categorizing the safety-critical events which in turn can increase their speed of choosing the adequate reaction. Thereby drivers adapt their driving behavior (like speed and strength of the pedal pressing) to the requirements of the currently relevant situation.

The results of the analysis of learning effects over the first trial without assistance (T1) and the following two trials with assistance (T2 and T3) showed that the absolute number of collisions decreased with the repetition of the W2 scenarios over T1–T3, yet without reaching significance. Nevertheless, the brake reaction time decreased significantly in all *scenarios* over the three *trials*, reaching the lowest amount in T3. However, this reduction differed between the *scenarios* as well as between the *trials*, since the initial brake reaction time levels already varied between the scenarios. For example, in the less critical scenario OH, the time benefit between consecutive trials decreased from 0.7 s to 0.6 s, whereas in the rather critical scenario PS, the time benefit dropped from 0.3 s to 0.1 s over time. Despite the brake reaction time being reduced with increasing experience over the trial repetitions, the brake reaction time improvement stagnated eventually (floor effect at around 0.8 s). This level might be hard to undercut by the drivers, even if more trials with the same scenarios were introduced, due to the drivers' needing a minimum of time for processes like perception, processing, decision making and action execution (Rogers et al., 2000).

Concerning the maximal applied brake force the *scenarios* differed, only the two W2 scenarios though significantly, while no learning effects were found. It seemed drivers quite intuitively knew what kind of reaction a situation required. Nevertheless, the levels of brake force seemed to interchange between the two W1 scenarios when drivers were assisted. Some adaption due to the assistance still seemed to take place. So in general the driving performance improved or stayed appropriate (in case of the applied brake force) over the three consecutive *trials*. Then again drivers might also compensate their consistent brake maximum by reacting faster. An earlier reaction can be less strong and still as effective.

Apparently, drivers learned to brake faster over time, but since the first trial was without assistance and the two following with assistance, this might be a combined result of the repeated scenario experience and the added assistance. In order to distinguish better between learning and assistance effects, the baseline trial T1 (without assistance) was additionally compared with the transfer trial T4 (with assistance) which contained new critical events. Although the collision frequency did not change, the brake reaction time improved with assistance in all scenarios even when the scenarios were unknown. However, the amount of reduction again depended on the *scenario* and naturally on the first-time reaction in T1. The two W1 scenarios differed more clearly than the W2 scenarios in their levels of brake reaction time, while the brake maximum levels differed more between the W2 scenarios and not the W1 scenarios. This might be due to the brake maxima changing their order between both W1 scenarios over the two trials again (T1 & T4). Without assistance drivers braked stronger in scenario OH (obstacle behind hill), whereas with assistance they braked stronger in scenario LS (lead vehicle stopping at straight road) as also found in the learning effect analysis between T1 and T2. Nevertheless, in none of the scenarios *trial* effects were found. The brake maximum was more affected by the safety-critical situations than the added assistance (especially in the W2 scenarios).

Consequently, drivers braked faster with assistance even in new situations with a rather constant strength. So the assistance generally has a positive effect on the brake reaction time as the comparison of trial T1 (without assistance) to T2 as well as to T4 (both with assistance) showed. This is in line with the result from an earlier study of Winkler et al. (2018a), which examined the same situations with and without warning support and also found positive driver assistance effects. Yet, the comparison of trial T1 to T4 also implied transfer effects, as the drivers already went through a learning phase with the assistance by the time they reached T4 and could try it out on a greater variety of scenarios than at the beginning of T2, when the assistance was still new and only the scenarios known to them. Therefore the transfer effect was analyzed separately by comparing T2 to T4 (both with assistance).

The results showed that although the drivers were new to the scenarios experienced in trial T4, they benefited from the knowledge gained through the preceding trials if their brake reaction was not already on a quite low level in T2 due to the added system support. In the *urgent warning* (W2) scenarios, which required an immediate driver response, the room for improvement was limited. For example, the brake reaction time in the most critical scenario PS (pedestrian crossing at straight road) of 0.8 s in T2 could hardly be beaten. Hence, it stayed the same in T4. Similarly, the collision frequency in the W2 scenarios did not change significantly over the *trials*. Due to the earlier warning onset in the *warning* (W1) scenarios asking for more moderate driver reactions, the time frame for improvements was broader. Hence, in these less critical scenarios the drivers' brake reaction time in T4 was significantly lower than in T2 even though the drivers already had scenario experience, but assistance experience was lacking. Hence while there was a transfer effect for the W1 scenarios, in the W2 scenarios drivers benefited equally from having either experience with the scenarios (not the assistance) or the assistance (not the scenario). However, in general the effect of an assistance system could be enhanced when drivers are granted practice with it. This learning can even be (partly) transferred to different situations with the same warning support as the comparison of T4 (unknown situations with known assistance) and T2 (known situations with unknown assistance) showed.

Moreover, the subjective evaluation of the two-stage warning system was positive. It was rated *rather high* to *very high* concerning its understandability and helpfulness. The *urgent warning* (W2) was rated significantly higher on these scales than the *warning* (W1), which might be due to its more activating character requiring a driver reaction compared to the more generally attention raising *warning*. Furthermore, it showed again that such rather generic warning symbols are well accepted. Besides, they allow to alert drivers even if the object detection is not yet 100% certain (since this is still work in progress, see e.g., Cordts et al., 2017; Diederichs et al., 2018; Schmidt and Färber, 2009) as contrary to a more specific warning symbol, which might display the relevant safety-critical object (see Winkler et al. (2018a)). However, the understandability should be further investigated in the case of the drivers' not receiving an instruction about the entire warning system as an extension to this experiment since this might likely be the case in the field. Distraction did not seem to be a problem of the analyzed warning system. Both warning stages were judged *rather low* on the distraction scale. The two-stage collision warning system also lived up to the drivers' expectations as induced by the instructions beforehand. The system acceptance measures usability and satisfaction were rated as similarly positive before and after experiencing the system during the entire test drive.

However, these results are subject to a number of limitations. First of all, the sample is limited in its representativeness as it was mostly constituted by university students with a lower mileage per year than an average driver. Furthermore, the number of data points in some comparisons was rather small, especially for within-subjects analyses involving scenario PI. For example, in the first trial about half of the drivers triggered the pedestrian crossing while they were still in the middle of the intersection. Their far too early brake reactions were mere corrective actions of their turning maneuver. Thus, the participants were often completely unaware of the passing pedestrian that was to act as critical event. Apparently, the drivers could have needed more training on how to steer in the driving simulator. Yet, the number of turns and tight curves was intentionally kept rather low to avoid simulation sickness, which drivers are particularly prone to in urban area driving as the experience from previous experiments showed. This dilemma inherent to driving simulation experiments still needs to be solved in the future.

Nevertheless, choosing a lab environment like the driving simulator for this experiment, compared to a field environment for instance, was still advantageous in many other regards. As described before, it allowed testing a driver assistance system in a controlled setting of repeated trials of various hazardous situations without endangering the participants or their surroundings. Furthermore, the results suggest that the driving simulator can provide a good training opportunity for drivers to gain experience with a warning system for safety-critical situations in a rather short amount of time. This in turn can maximize the effectiveness of such driver assistance systems and further increase traffic safety. However, it still remains to be seen whether these learning effects can be transferred to the own car in every day traffic situations when drivers might also be less attentive than under observation. Yet, as transfer to new situations was found in this study, it seems likely that there will be at least some positive transfer from the driving simulator to driving in real traffic.

Otherwise, it has to be pointed out that the found effects of system learning cannot totally be distinguished from situational learning. Regarding behavioral changes over time is always a trade-off. Either the to be compared data points are collected from controlled trials of exact same circumstances that rule out other influential factors (as only possible in laboratory settings), but bear the risk of participants adapting to the situation itself rather than the manipulation (the assistance), or the trials slightly differ which is more realistic, but hinders causal interpretations of the manipulation. This experiment followed the approach of rather exact repetitions, but limited the number of repetitions so that situational adaptions might be minimized in favor of system learning. Nevertheless, this issue has to be considered when regarding the results.

Another question concerns how the beneficial system effects might change when drivers experience system errors like false or unnecessary alarms. In this experiment, the system always functioned perfectly in order not to mask the other focused effects. With the generic design of the used two-stage collision warning false alarms should be less likely, whereas unnecessary or unnecessarily urgent alarms might be more of an issue. Especially urban areas challenge not only drivers but also the reliability of assistance systems (their detection and anticipation accuracies) as the frequency, diversity and complexity of their traffic situations is demanding. If drivers receive warnings in situations which they do not evaluate as safety-critical, for example because the alerts are given too early, this might limit the positive effects of the assistance found in the examined hazardous situations and thus reduce its usefulness (e.g., the cry-wolf effect, see Breznitz, 1983 or also Abe and Richardson, 2006; Horowitz and Dingus, 1992). However, as the present experiment showed, drivers adapt their behavior also according to the situation requirements (different reactions although the same warning was given), cases of improper alarms might not be overly disturbing for drivers. The assistance might still help them to decide and act faster if there really is a danger requiring their attention or intervention. Although the influence of incorrect alarms might also depend on the ratio of proper to improper alarms (Wickens and Dixon, 2007), besides less favorably subjective ratings drivers still benefit from an assistance (even if less reliable) compared to no assistance (Naujoks et al., 2016). Alerts of less urgency or intrusiveness are therefore recommended. This agrees perfectly with the idea of warning drivers in successive warning stages of adapted urgency and thus supports the multi-stage warning approach. However, it might also be interesting to introduce another trial without assistance in the end of an experiment, comprising a completely new scenario, to measure whether or how much the drivers improved their reactions altogether (e.g., Bueno et al., 2014).

Additionally, there might be effects of risk homoeostasis (Wilde, 1988, 2014). If drivers learn that for every critical situation there is a warning, negative adaptations might occur. For example, after a while of training, drivers might rely too much on the assistance. This might lead to drivers underestimating situation criticalities which might raise problems like inappropriate driver reactions or in the worst case a total lack of reaction readiness if not presented with a warning. If the system then fails to detect an upcoming safety-critical event, drivers trained with the assistance might have even more difficulties reacting adequately than drivers without system experience as they got too used to reacting only when alerted. However, as the warning system still depends on the reactions of the drivers and does not act autonomously, it seems likely that drivers will remain alert und ready to react. Nevertheless, this should definitely be examined in future research.

Furthermore, other age groups should be regarded to see how for example older drivers can benefit from the system. It would be interesting to investigate how much they could still improve their brake reaction time when trained with the warning system since learning takes increasingly longer with age and other driving related skills also rather deteriorate (e.g., Rackoff, 1974; Schlag, 1993). With respect to the demographic development of people growing older and older, their mobility and safety could be enhanced strongly with such systems, especially when provided with a learning phase.

Consequently, the proposed multi-stage warning approach has high potential to support drivers for collision avoidance in various safety-critical traffic situations due to its adaptive and rather generic character. Despite it being well understood and accepted by the drivers, the driving behavior measures also indicated a safety benefit of driving with the two-stage warning system. The drivers initiated earlier brake reactions with the system over time even in new situations and applied situation adaptive brake forces throughout the experiment. The escalation of safety-critical situations was slowed down so that in case of an unavoidable collision its impact would be reduced for all sides. In general, drivers are able to react to the requirements of any situation.

However, the assistance insures they have enough time to do so. Thus, the two-stage collision warning can contribute to making the roads safer and preventing injuries. Even though nonessential for their effectiveness, practice with advanced driver assistance systems is recommended for drivers (e.g., in a driving simulator) to maximize their benefits.

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