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How to warn drivers in various safety-critical situations – Different strategies, different reactions

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ABSTRACT

Technological advances allow supporting drivers in a multitude of occasions, ranging from comfort enhancement to collision avoidance, for example through driver warnings, which are especially crucial for traffic safety. This psychological driving simulator experiment investigated how to warn drivers visually in order to prevent accidents in various safety-critical situations. Collision frequencies, driving behavior and subjective evaluations of situation criticality, warning understandability and helpfulness of sixty drivers were measured in two *trials* of eight *scenarios* each (within-subjects factors). The *warning type* in the head-up display (HUD) varied (between-subjects) in its strategy (attention-/reaction-oriented) and specificity (generic/specific) over four warning groups and a control group without a warning. The results show that the scenarios differed in their situation criticality and drivers adapted their reactions accordingly, which underlines the importance of testing driver assistance systems in diverse scenarios. Besides some learning effects over the trials, all warned drivers showed faster and stronger brake reactions. Some warning concepts were understood better than others, but all were accepted. Generic warnings were effective, yet the warning strategy should adapt to situation requirements and/or driver behavior. A stop symbol as reaction generic warning is recommendable for diverse kinds of use cases, leading to fast and strong reactions. However, for rather moderate driver reactions an attention generic approach with a caution symbol might be more suitable. Further research should investigate multi-stage warnings with adaptive strategies for application to various situations including other modalities and false alarms.

1. Introduction

Advanced driver assistance systems (ADAS) such as warnings and interventions, lateral and longitudinal control or action recommendations can contribute to traffic safety and driving comfort, as many studies have shown (e.g., Bengler et al., 2018; Cicchino, 2017; Hanowski et al., 1999; Hofauer et al., 2018; Jones and Hansman, 2007; Lee et al., 2002b; Rittger and Götze, 2018; van Driel et al., 2007). Yet, many ADAS are tested in very specific use cases. This makes them perfect in these situations, but their adaptation to other use cases is limited. Especially in urban areas the variety of situations drivers are confronted with increases exponentially. Therefore the human-machine interface (HMI) of ADAS should be designed in a way that allows drivers to understand and handle all kinds of situations successfully without further strain due to understanding, prioritizing or differentiating a number of ADAS at the same time. Thus, integrating all ADAS into one HMI solution which adapts its output according to situation and driver needs seems ideal. Such an *"HMI tool kit"* (Drüke et al., 2018) or so called *"information/warning/intervention strategies"* (Hesse et al., 2011) were for instance focused in research projects like "UR:BAN" (Bengler et al., 2018) or "interactIVe" (Alessandretti et al.,2014).

As part of an integrative HMI, collision warnings would be of highest priority, overlaying all other ADAS, in case of a safety-critical situation (hazard on collision course with the drivers' vehicle). They support drivers' reactions by alerting them to impending hazards in order to reduce crash rates and severities. By implementing a continuum of different urgency levels for accident prevention or mitigation (multi-stage warning approach), drivers are always provided with exactly the support they need in the respective safety-critical situations (see Campbell et al., 2007; Diederichs et al., 2010; Jones and Hansman, 2007; Naujoks and Neukum, 2014; Werneke et al., 2014; Winkler et al., 2016, 2018a, 2018b; Zarife, 2014). Initially, they might receive an unintrusive *information* or *early warning* about an upcoming situation. With increasing criticality of a situation this might escalate to more *urgent warnings* that ask for stronger driver reactions in later stages. Finally, the vehicle might even *intervene* automatically. Designing collision warnings is therefore a complex and challenging task of high

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significance.

Besides technical and environmental factors, like limited time frames and hazard recognition (its type, relevance, anticipated movement and accuracy), user-centered questions such as how to present the crucial information to drivers for maximum benefit also merit consideration. Environments like urban areas with a maximum of traffic variance are particularly demanding for drivers and car manufacturers (for more information on the interaction of complex traffic situations and driver assistance in urban areas see the underlying research project “UR:BAN”; Bengler et al., 2018). Urban areas bear a lot of distracting stimuli for drivers, while high traffic and information densities restrict decision periods to a minimum. All kinds of road users (e.g., pedestrians, motorists and cyclists) interact at various locations (e.g., at intersections, straight roads or curves) with different speeds, creating a multitude of potentially safety-critical situations. Hence, the frequent occurrence of hazardous situations makes accidents very likely, especially due to driver errors like attention misallocation, wrong expectations or distraction, tailgating, speeding or rule violations and loss of vehicle control (Bhatia, 2003; Great Britain Department for Transport, 2015; National Highway Traffic Safety Administration, 2008; Singh, 2015; Summala, 1996).

As accident analyses of German road traffic show (Statistisches Bundesamt, 2014), about three quarters of all police-recorded accidents since 1991 are allotted to urban areas. They also account for the main part of accidents with personal injuries (ca. 69% in 2011, 2012 and 2013). With increasing urbanization, urban areas and their complex situations come more and more to the fore of current research activities, even more so as already existing ADAS are mainly designed for situations with higher speed limits like rural roads or highways. Thus, it is important to analyze the interaction between safety-critical urban situations and ADAS like forward collision warnings (FCW).

However, each situation has its own requirements on how and in which time frame it should be handled by the drivers without resulting in a collision. So, the question arises which driver reaction is best in a variety of situations. Most drivers show brake reactions in safety-critical situations, rather than for example steering reactions (evasive maneuvers) or a combination of both maneuvers (Powelleit and Vollrath, 2018), although steering might be better when braking distances are insufficient (Moeller and Frings, 2014; Schneider et al., 2015). Moreover, not all situations are of the same criticality (for further information on hazard perception and characterization see Borowsky and Oron-Gilad, 2013 or Crundall et al., 2012). There are cases when reactions from mere attention reallocation (to be ready to react) to speed reduction, gas release or even moderate braking might suffice to resolve safety-critical situations such as in early warning stages (e.g., in case of slow-moving traffic in some distance, see Winkler et al., 2016). Hence, these warnings could also focus on raising or guiding drivers' attention (gradual behavior adjustment) when there is more time before hazards are encountered or situations become even critical (e.g., due to early object recognition based on car2x communication technology, see Naujoks and Totzke, 2014; Tan and Huang, 2006). Such early warnings though could raise the drivers' attention generally or provide more details about the hazard (e.g., its type, location or distance) in order to direct the drivers' attention distinctly. However, the best strategy is yet unclear.

Additionally, driver warnings could specify in safety-critical situations whereupon drivers should concentrate their attention in earlier warning stages (attention specific) or how to react in more urgent warning stages (reaction specific; see Cao et al., 2010; Lee et al., 1999). Would this information be helpful for drivers or too much under time pressure? That is to say, differentiating the alerts and selecting a steering reaction instead of a highly automated brake reaction, as for example recommended by reaction specific warnings, might add to drivers' already high mental workload. Should generic driver warnings (reaction/attention generic) thus be favored? On the one hand, generic warnings facilitate time-saving automatic driver responses (like alerted visual scanning or emergency braking) since they convey less information. On the other hand, universal warning cues or master alerts for different kinds of situations might lack important details for the understanding of the situation, which could lead to confusion and slower reactions (Campbell et al., 2004). Thus, the question of the warning specificity arises. Furthermore, warning strategy and specificity might interact, affecting the drivers' acceptance as well as their performance (processing and reaction execution; Zarife, 2014). Therefore, the overall aim of this paper is to examine which types of driver warnings (varied in strategy and specificity) suit various safety-critical situations optimally.

A driving simulator study of Naujoks and Neukum (2014) investigated the specificity of driver warnings twofold (*conflict-specificity*: indicating hazard type or not; *direction-specificity*: indicating hazard direction or not) besides their timing. According to them, the specificity rather influenced the warning usefulness than the driving behavior. However, they concentrated more on attention-oriented driver warnings at an earlier, advisory level. Whereas the present study excluded the timing question by adapting the warning onset to the different safety-critical situations, but extended the specificity question to reaction-oriented warnings at later, more urgent stages.

Similarly, the video-based experiment of Thoma et al. (2009) identified no differences due to the warning specificity in the drivers' reaction time to safety-critical situations. Contrary to the present experiment, their participants did not actually drive themselves, but merely watched videos in the driving simulator. This enabled the drivers to pay much more attention on every detail of the scene than when actually driving and thus might have facilitated the hazard detection. However, in both mentioned studies and another study of similar results by Brown et al. (2017) the warning visualization was accompanied by an acoustic warning signal. Despite it being unobtrusive, according to Naujoks and Neukum (2014), it might still have masked some effects of the specificity of the warning visualizations. Therefore, the warning concepts developed in this study used the visual modality exclusively, without additional acoustic or haptic warning modalities.

On the one hand, the visual modality can transfer very complex and detailed information (like different levels of specificity). On the other hand, drivers are already visually strained by the driving task itself (Scott and Gray, 2008; Powelleit and Vollrath, 2013; Rockwell, 1972; van der Horst, 2004). Even more load on the visual channel might be critical (especially when higher encoding effort is necessary). Drivers' glances might linger for too long on the warning display so that actually critical objects or situations might go unnoticed until it is too late. Besides, drivers might be distracted by secondary tasks, their gaze directed away from the road or their eyes even closed (as during saccades or when sleepy). In these cases a visual warning might not reach drivers' awareness so that an auditory alarm might be preferable. However, auditory alarms are more annoying, especially when experienced frequently (Campbell et al., 2007; Ho and Spence, 2008; ISO, 2005; Lerner et al., 1996b; Marshall et al., 2007), as it was the case in the present study and is common in real traffic with advanced in-vehicle driver warnings of multiple stages. For further research on the specificity of acoustic warning signals see Cummings et al. (2007); Klein et al. (1992); Spence and Driver (1994); Xiang et al. (2016) or of visual and acoustic warnings in comparison see Schwarz and Fastenmeier (2017).

Consequently, it might be best to integrate the advantages of every modality in a multi-modal warning approach (see Biondi et al., 2017; Cao et al., 2010; Kramer et al., 2007; Liu et al., 1999). Varied combinations of modalities are thinkable for different warning stages. However, the scope of this study was to primarily investigate the design of visual alerts. To be beneficial, warning visualizations should be rather simple, intuitive and easy to understand (Kiefer et al., 1999; Lerner et al., 1996a, 1996b) since an increase in the cognitive demand of warnings increases drivers' reaction and detection time (Wolffsohn et al., 1998). Laughery (2006), Wogalter et al. (2002) and Young (1991) recommended using color and icons or pictorials to augment the salience and thus the noticeability of visual warnings. Moreover, familiar traffic signs can help drivers to process, understand and in the end handle safety-critical situations better (Alves et al., 2013; George et al., 2012; Ng and Chan, 2008; Payre and Diels, 2018; Plavsic et al., 2009). Therefore, colored traffic signs visualized all driver warning concepts. Their red color and particular shape were to alert drivers additionally, as suggested by Bhatia (2003), Campbell et al. (2004) and Young (1991).

Where to locate in-vehicle driver assistances is also discussed in a lot of studies (e.g., Benmimoun et al., 2007; Lee et al., 1999; Tsimhoni et al., 2001; Wittmann et al., 2006; Yoo et al., 1999). This study used a head-up display (HUD) to visualize all warning symbols. In contrast to an instrument panel display or other so called head-down displays (HDD), a HUD maintains the drivers' gaze directed towards the road, even when perceiving warnings, as they are projected into the windshield right above the engine hood and overlap with the road reality in their field of view (see Hanowski et al., 1999; Horrey et al., 2003; Lee et al., 1999; Luoma and Rämä, 2002). This renders drivers more likely to see an external event needing their immediate attention, such as a vehicle in their path (Alves et al., 2013; Tretten et al., 2011, also see Wickens and Long, 1994), unless cognitive capture or visual masking occur, for example due to visual clutter or contrast interference (Gish and Staplin, 1995; Green et al., 2008; Ward and Parkes, 1994). However, if not designed user-friendly or integrated into the driving task HUDs might also increase drivers' work load which in turn might narrow their attention (also called cognitive, visual or perceptual tunneling), shrink their field of view and thus result in impaired peripheral detection (see Dirkin, 1983; Gish and Staplin, 1995; Mackworth, 1965; Sanders, 1970; Williams, 1985). In order to avoid such issues, the displayed information should be intuitively understandable so it can be processed rapidly without distracting or straining the drivers additionally. Since HUDs merely require eye accommodation, but no eye or head movements, using them to present collision warnings can reduce drivers' response time considerably and thus mean significant safety benefits (Ablaßmeier et al., 2007; Azuma, 1997; Watanabe et al., 1999).

In order to evaluate the different warning concepts, situations created to become safety-critical were implemented in the driving simulator. According to accident analyses, the three most common accident types in urban areas are caused by vehicles turning into a road or crossing it (26%), moving along in carriageway (21%) and vehicles turning off a road (16%), making up almost two thirds of all traffic accidents on German urban roads in 2013 (Statistisches Bundesamt, 2014). However, the most fatalities are entailed by vulnerable road users crossing the road (27%), which is why these situations are usually rated as very critical. Hence, similar constellations as described in the accident analyses were realized. Some were newly elaborated. Others were used from previous studies (Kazazi et al., 2016; Muhrer and Vollrath, 2010; Powelleit and Vollrath, 2018; Werneke and Vollrath, 2012). For example, Kazazi et al. (2016) developed and analyzed safety-critical incidents with respect to how drivers react and how they can be supported by systematic collision warnings. In sum, eight scenarios (each including one safety-critical situation) were implemented in the present study. This is a far greater number than in most ADAS evaluations. Usually only one type of safety-critical situation is regarded (e.g., Ben-Yaacov et al., 2002; Benmimoun et al., 2007; Horowitz and Dingus, 1992; Lee et al., 2002b; Werneke and Vollrath, 2013), which makes general recommendations, for instance on how to design warning concepts, rather difficult (if feasible at all). Kramer et al. (2007) actually tested a collision avoidance system (yet in HDD not HUD) in different driving situations, but focused on higher speeds without varying the safety-critical object contrary to this study. However, situations in the urban context are much more diverse than on highways. This diversity was accounted for in the present driving simulation, which additionally constrained expectancy effects.

Drivers were exposed to every scenario twice to control for learning effects as repeated event exposure can influence drivers' brake reactions (Aust et al., 2013). Shinar and Schechtman (2002) and Ben-Yaacov et al. (2002) also detected learning effects for drivers using headway feedback, leading to safer distances over time. Likewise, Koustanaï et al. (2012) found that familiarization with a FCW improved drivers' system interaction and reaction time. Hence, similar effects were expected for this study. Besides, experiencing the warning concept in the same scenario twice, allowed drivers to appraise the warning concept more thoroughly for the subjective evaluations.

Summing up, this driving simulator study used eight safety-critical situations (within-subjects factor *scenario*) in repetition (within-subjects factor *trial*) to evaluate different warning concepts (between-subjects factor *warning type*) which support drivers in collision avoidance. The aim of the study was to explore whether one warning cue can be used for different kinds of safety-critical situations, as found in the complex environment of urban areas. Driving with a warning was to improve the driving behavior over no warning being present. It was assumed that the *warning type* would influence the drivers' behavior and subjective ratings, while its suitability might vary with the *scenario*.

2. Method

2.1. Driver warning

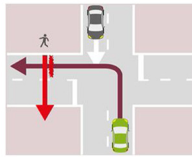
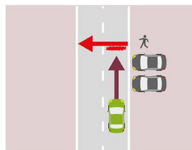
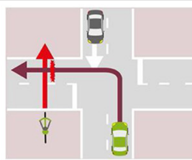
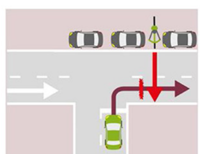
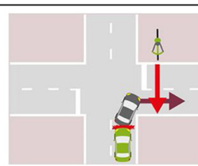
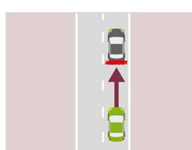
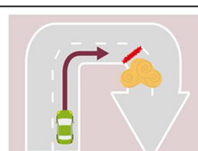
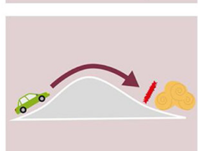
The basic aim of the examined warning concepts was to support drivers in avoiding and mitigating collisions with safety-critical objects. They were conveyed visually without additional acoustic or haptic signals to eliminate masking the actual effects of the different warning visualizations. The warnings were presented driver-centered in a simulated multicolor HUD right above the engine hood, measuring maximum 21 x 21 cm (6° visual angle).

As Table 1 shows, four different *warning types* were developed according to pilot tests within the HMI experts of the research project "UR:BAN" (see Winkler et al., 2018b) and literature reviews (see 1 Introduction; e.g., Laughery, 2006; Laughery and Wogalter, 2006; Naujoks and Neukum, 2014; Thoma et al., 2009; Wogalter et al., 2002). They were presented to independent groups of subjects. While two of them were to elicit an immediate driver reaction, either braking or steering, the other two were to direct the drivers' attention towards the safety-critical objects and enable them to react adequately (warning strategy: reaction- vs. attention-oriented). It was found that (red) warning triangles attract drivers' attention, but are of a more informative than activating character compared to other symbols such as stop symbols. Thus, warning triangles were used for an attention-oriented strategy and stop symbols for a reaction-oriented strategy. In both strategies, warnings could either be generic or specific, with the

Table 1
Implemented *warning types* as visualized in the head-up display (HUD).

Warning type	Visual presentation
Control (C)	None
Reaction generic (RG)	
Reaction specific (RS)	
Attention generic (AG)	
Attention specific (AS)	

Table 2
Textual and pictorial depiction of the eight scenarios with the type of the safety-critical object, the location of its encounter and the warning onset.

Object	Location	Picture	Description	Warning onset
Pedestrian (P)	Intersection (I)		When turning left at an uncontrolled intersection with oncoming traffic (which has the right of way), a pedestrian emerges from a visible crowd at the farther end and crosses the ego vehicle's turning path (accelerating to 4 m/s)	3 m behind waiting line (3 m behind pedestrian activation point)
	Straight road (S)		While driving straight ahead on a one-way road, a pedestrian hidden by parking vehicles crosses the ego vehicle's path from right to left (green area) with 2 m/s *(evasive maneuver possible)*	23 m before crossing point (same as pedestrian activation)
Bicyclist (B)	Intersection (I)		When turning left at an uncontrolled intersection with oncoming traffic (which has the right of way), a bicyclist crosses the ego vehicle's path from left to right with 10 m/s (contrary to allowed direction)	3 m behind waiting line (same as bicyclist activation)
	T-junction (T)		When turning right at an uncontrolled t-junction with oncoming traffic (which has the right of way), a bicyclist hidden by parking vehicles crosses the ego vehicle's path from left to right with 10 m/s	20 m before crossing point (same as bicyclist activation)
Lead vehicle (L)	Intersection (I)		When following a lead vehicle indicating a right turn at an uncontrolled intersection (which decelerates with 2 m/s² to 8.5 m/s), it stops suddenly for a bicyclist crossing from left to right *(evasive maneuver possible)*	30 m before lead vehicle's full stop in front of the crossing bicyclist
	Straight road (S)		On a straight road without oncoming traffic, a lead vehicle suddenly brakes (which decelerates with 25 m/s² to 3 m/s) without any warning or reason *(evasive maneuver possible)*	7 m before the lead vehicle starts to brake
Obstacle (O)	Curve (C)		When driving straight ahead without oncoming traffic, a hay bale blocking the ego vehicle's path suddenly becomes visible after being hidden from drivers' sight by a curve *(evasive maneuver possible)*	75 m before the obstacle location (when it becomes visible)
	Hill (H)		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	70 m before the obstacle location (when it becomes visible)

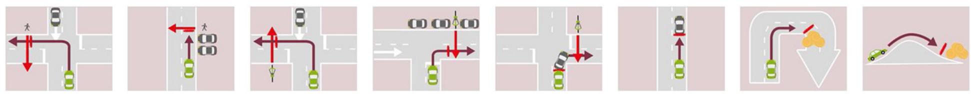
specific version giving more information to benefit drivers' response selection, for example by displaying the type of hazardous object for more definite attention allocation (attention specific) or the kind of required reaction for more successful collision avoidance (reaction specific).

According to that, the reaction specific (RS) warning advised drivers to stop (via a stop sign) or to swerve around the safety-critical object (via a "steer symbol", see Table 1) when an evasive maneuver was possible (as indicated in Table 2). The reaction generic (RG) warning used a stop sign in all safety-critical situations. While the attention generic (AG) warning displayed a red warning triangle with an exclamation mark (caution sign), the specific version (AS) depicted the relevant safety-critical object within a warning triangle (pedestrian, bicyclist, lead vehicle or obstacle, see Table 1). In order to examine the overall effect of the different *warning types*, a control group without any warning was included as a baseline. For further aspects of the experimental design, see Table 3.

In general, it was difficult to agree on reaction-oriented symbols. For example, a normal arrow traffic sign (mostly white on blue in Germany) as "steer symbol" was considered not reaction-prompting enough. Therefore, it was combined with a red-striped traffic cone to display an actual obstacle that has to be avoided like in a slalom course. Additionally, developing a completely generic reaction-oriented warning symbol (not speaking of other generic non-symbolic options

Table 3
Experimental plan of the within-subjects factors *trial* (2) and *scenario* (8), and the between-subjects factor *warning type* (5).

Trial	T1 (identical to T2 regarding the factors *scenario* and *warning type*)							
Scenario / **Warning type**	PI	PS	BI	BT	LI	LS	OC	OH
Control (C)	-	-	-	-	-	-	-	-
Reaction generic (RG)	STOP	STOP	STOP	STOP	STOP	STOP	STOP	STOP
Reaction specific (RS)	STOP		STOP	STOP				STOP
Attention generic (AG)								
Attention specific (AS)								



like LED bars) was challenging, which is why the stop symbol is employed in the reaction generic and specific warning group.

2.2. Driving simulator and scenarios

The experiment was conducted in a static medium fidelity driving simulator of the Technische Universität Braunschweig (see Fig. 1). It comprises a seat box with typical car interiors like car seats, a steering wheel with force feedback, accelerator and brake pedals as well as three LCD screens serving as rear-view mirrors. Surrounding the seat box at about 2.1 m distance from the driver's seat are three screens (ahead: 1.85 m x 2.10 m, left and right: 1.85 m x 2.20 m), onto which three beamers (1400 × 1050 px resolution) project the virtual scenery, created by the driving simulation software SILAB (from WIVW, Krüger et al., 2005; see www.wivw.de). Thus, the drivers are provided with a 180° field of view. Complementing the rather realistic driving impression comparable to sitting in a real car, acoustical simulations of traffic sounds like wind and engine noises complete the driving simulation. Drivers had full lateral and longitudinal control over the vehicle.

The different critical situations were embedded into an urban area with a speed limit of 50 km/h. The main part of the track was more or less straight, so as to reduce the risk of simulation sickness. Left or right turns were indicated by a voice output and an arrow near the speedometer in the instrument panel. Altogether eight scenarios were implemented, each containing a safety-critical object. The scenarios differed by the object type (pedestrian, bicyclist, lead vehicle or hay bale), its behavior dynamics ((crossing) direction and distance) and the location of the encounter (intersection, straight road, curve or hill). Some scenarios were adopted from previous studies (Kazazi et al., 2016; Muhrer and Vollrath, 2010; Powelleit and Vollrath, 2018; Werneke and Vollrath, 2012). Others were newly created according to accident analyses (e.g., Great Britain Department for Transport, 2015; National Highway Traffic Safety Administration, 2008; New Zealand Transport Agency, 2014; Statistisches Bundesamt, 2014). Between the scenarios drivers went mostly straight in normal urban traffic without further critical incidents. Table 2 gives an overview of the eight scenarios (whereby the vehicle of the participant is referred to as "ego vehicle"). It indicates if the situation preferred an evasive maneuver by the drivers, denoting in which scenario the reaction specific warning displayed the "steer symbol". Even though a steering reaction might be more advantageous in some critical situations, it is hard to evoke them in drivers (see also Powelleit and Vollrath, 2018). Most drivers rather brake upon potential hazards (Adams, 1994; Malaterre et al., 1988). Nevertheless, this study included scenarios that welcomed evasive maneuvers in order to test the specificity of the reaction-oriented strategy.

Table 2 also specifies when the warnings were activated. The triggering of the safety-critical object and the warnings was chosen due to pilot studies and based upon the ego vehicle crossing specified landmarks. Due to technical constraints, the complexity and the diversity of the scenarios, time-to-collision thresholds could not be used in this study, but hopefully in future studies. The activation of the safety-critical objects (e.g., pedestrian moving, lead vehicle braking etc.) was to result in critical situations and thus create a need for warnings in the first place. The warnings should then help drivers to react adequately in order to avoid collisions with a safety-critical object or to keep situations from becoming really critical. In order to apply the warning concepts to a wide variety of situations, the eight scenarios varied with regard to the severity of the situation. For example, scenario PI asked drivers for a more immediate de-escalation reaction than scenario OH. In general, the scenarios bearing higher risks of fatalities and being more time-critical were expected to be of a comparatively high situation criticality. However, a rather explorative approach was followed in this matter. Achieving similar levels of criticality within a scenario for every participant was a challenge in this experiment, as the driver behavior could not be completely controlled. This is especially relevant right before the hazard activation. For example, drivers naturally keep individual safety-distances to lead vehicles during following, so that a sudden braking of a lead vehicle can have varied impacts and thus can result in situations of diverse criticality. Even synchronizing the lead vehicle's speed entirely to the ego vehicle's in pretests did not solve this problem. Drivers only decelerated more and more, eventually being unnaturally slow. Hence, this knowingly accepted random within-subjects variation has to be respected when interpreting the results.

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

Table 4
Dependent measures analyzed in this paper.

Objective variables	Unit	Description
Collision frequency	%	Number of times the ego vehicle crashed into the safety-critical object on encounter
Brake reaction time	s	Time from warning onset (notional in the control group) until the brake pedal is pressed (≥0.2 s, including collision incidents)
Brake maximum	%	Maximum pressing of the brake pedal after warning onset until the speed is zero or the brake pedal is released again (in percent of the sample maximum)
Subjective variables		**Description [1 (*very low*, -) … 15 (*very high*, +); Heller, 1982]**
Situation criticality		"How critical was the experienced situation?"
Warning understandability		"How understandable was the warning in the experienced situation?"
Warning helpfulness		"How helpful was the warning in the experienced situation?"

2.3. Experimental design

The experiment followed a mixed design with three independent variables (see Table 3). In order to examine the effects of the four different *warning types* in comparison to a control group (see Table 1), a between-subjects design was used for the independent variable *warning type* (5). Thus, all drivers experienced the same kind of warning as assigned to their group (or none in the control group) in every one of the eight scenarios (within-subjects factor *scenario* (8), see Table 2). Each scenario was driven twice by every driver (within-subjects factor *trial* (2): T1 and T2). So the drivers encountered critical events sixteen times in total. The order of the eight scenarios was randomized to control for time effects. According to the *warning type* the five driver groups are described as no warning (C), reaction-oriented generic (RG), reaction-oriented specific (RS), attention-oriented generic (AG), attention-oriented specific (AS, see Tables 1 and 3). As for the RS warning, drivers received a stop sign in the scenarios PI, BI, BT and OH, but a "steer symbol" in the scenarios PS, LI, LS and OC as steering around the safety-critical object was deemed more appropriate. The AS warning triangle depicted a pedestrian in PI and PS, a bicyclist in BI and BT, a car in LI and LS or a traffic cone in OC and OH to represent the relevant safety-critical object depending on the scenario (see Table 3).

In order to describe the driver reactions to the warnings, the entire driving behavior (e.g., position, speed, pedal and steering wheel activity) was logged at a frequency of 60 Hz by the simulation software SILAB (from WIVW; Krüger et al., 2005) of the driving simulator. Three of such objective parameters were investigated in this paper (see Table 4). With the major aim of the warnings to increase the traffic safety, the number of collisions (later transformed into percentages), the brake reaction time and the maximal applied brake force (brake maximum) were analyzed. Contrary to plan, the steering behavior could not be examined as drivers hardly showed any steering reactions (see 4 Discussion). Moreover, gaze behavior data was recorded via Dikablis eye tracking glasses and the according software from Ergoneers (Ergoneers, 2009; see www.ergoneers.com) in order to see what drivers fixate when, in which order and for how long (e.g., the road, the hazard or the warning). With a view to investigate how the warnings supported directing the driver's attention, the gaze behavior was evaluated with the automated software (D-Lab). However, since the HUD often overlaid the safety-critical object in the drivers' field of view and even manual evaluation proved to be on the verge of speculation in many cases (especially with bigger surface hazards), further analyses of the gaze behavior were refrained from for now. Nevertheless, some results for the most critical scenario PS (pedestrian crossing a straight road) can be found in Winkler et al. (2015).

In order to measure the acceptance of the warning concepts by the drivers, subjective evaluations were conducted, including questions on how well the drivers understood the meaning of the warnings and how helpful the warnings were (see Table 4). Additionally, drivers rated the situations in order to examine to what extent the scenarios differed in their criticality (manipulation check). All three subjective ratings followed a two-stage procedure. Drivers first chose one out of five labeled categories and then refined their rating by selecting one out of three subcategories (-, 0, +) on the 15-point rating scale (see Fig. 2; Heller, 1982). This rating was then transformed into numbers from 1 to 15 (*"very low"* to *"very high"*). Afterwards a brief interview verified the understanding of the warnings' meanings.

2.4. Participants

Out of sixty-six drivers recruited through flyers, mailing lists and an existing pool of simulator drivers, six had to be excluded due to simulation sickness in the simulator training required for participation, resulting in a total of sixty drivers (27 female, 33 male, M = 23.7 years, SD = 3.7 years) completing the test. Their driving experience was on average 5.7 years (SD = 3.6 years). Their annual mileage was mainly less than 3000 km since a large amount of drivers was university students without a car of their own. All participants had normal or corrected-to-normal visual acuity and were compensated for successful participation with 12 € or course credits (if psychology students).

2.5. Procedure

After a welcome, participants were instructed in written form about the objectives of the experiment (*"investigation of driving and gaze behavior as well as subjective ratings in complex urban situations to derive driver assistances")*. They provided informed consent by signature and filled in a demographic questionnaire. All participants drove a training drive of 15 min to familiarize with the simulator as they would with a new car. Then they received two more instructions: (1) indicated that critical situations might occur (*"You will drive through several urban scenarios now, from which critical situations might arise."*) and (2) introduced the subjective rating procedure. The drivers with warning support were additionally instructed that they were assisted by HUD collision warnings. The exact design though was not further explained to test for intuitive understanding. Then the test drive followed, comprising two ca. 15 min trials of eight scenarios each (T1 and T2), interrupted only by a short break. After every scenario participants came to a short halt (as initiated by a banner on the front screen) to rate three subjective items on a touch screen in the center panel at the height of a car radio. The experiment concluded with a brief interview to verify the actual understanding of the warning symbols. Finally, the drivers were thanked and compensated for their participation. The entire experiment lasted about one and a half hour.

2.6. Data analysis

For the data analysis IBM SPSS Statistics 23 was used. At first, the subjective ratings of the situation criticality were analyzed by a mixed design ANOVA (with post-hoc pairwise comparisons) including the two within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type*. This served as manipulation check of whether the

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

Fig. 2. Two-stage rating scale by Heller (1982) to measure all subjective variables.

scenarios actually differed from each other and allowed ordering the scenarios in a sensible way. Subsequently, the collision frequency was investigated by a binary logistic regression within the framework of generalized estimating equations (GEE), in order to analyze possible main effects of the three fixed-effect factors *trial*, *scenario* and *warning type*. No interaction terms were included in the model (failure to converge on all criteria). The GEE regarded participants as a random effect and applied an exchangeable covariance structure. Compared to a logistic regression, the GEE framework allows predicting categorical variables (like collision: yes/no) based on repeated-measures data.

In order to investigate the drivers' brake behavior, the brake reaction time and brake maximum were employed. However, in some occasions decelerating merely by releasing the gas pedal, without actually pressing the brake pedal, was a sufficient reaction. Hence, in almost 16% of all safety-critical object encounters the drivers did either not initiate a brake reaction or a very late one, so that these data were treated as outliers and thus excluded from the data analysis (brake reaction time cutoff value of 2.9 s at a g-level of 3.0). This case occurred particularly often in scenario PI, LI and both bicyclist scenarios (see Table 5). Other times participants reacted before the warning onset or in less than 0.2 s, which was assumed to be the minimum time to brake upon the warning presentation. Primarily scenario LI fell into this category, with half of the data points being lost to these circumstances (see Table 5). All of the problematic scenarios featured an intersection. That is to say, drivers might have already slowed down in anticipation of approaching a complex situation by the time the warning appeared or were still driving slowly while crossing the intersection not necessitating a (fast) brake reaction. All these cases were excluded from the examination of the brake reaction time and brake maximum, respectively. Overall 77% of all data points were included for both parameters (see Table 5). The number of participants (*n*) included per group is hence always given at the bottom of a chart and has to be born in mind when interpreting the following results of the brake reaction time and brake maximum. Of course, certain scenarios like LI or BT could have been excluded from the analysis entirely due to the small number of useable data points, but as the effects did not change either way, they were further included in favor of a more thorough picture over all scenarios.

Due to the dissimilar numbers of participants in the groups an unbalanced model was used for data examination. Therefore, the brake reaction time and maximum were analyzed by a linear mixed model (based on restricted maximum likelihood (REML) estimations), referring to the participants as a random effect. Regarding the two within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type* as fixed effects all possible two-/three-way interactions and the three main effects were included in the model. Compound symmetry was chosen as the repeated covariance type. Finally, like the situation criticality the subjective ratings of the warning understandability and helpfulness (comprising only the four groups receiving a warning, thus excluding the control group without a warning) were analyzed by two mixed design ANOVAs (with post-hoc pairwise comparisons) including all three factors (*trial* and *scenario* as within-subjects factors; *warning type* as between-subjects factor).

All presented means are given with 95% confidence intervals (CI) as margins of error. If sphericity was violated, the Greenhouse-Geisser corrected degrees of freedom were used. For significant results of the ANOVA and the GEE, η^2 or r respectively, are given as measures of the effect size. A significance level of $p \leq .05$ was adopted in all statistical tests. All post-hoc pairwise comparisons were Bonferroni corrected. Finally, the results of all dependent measures are accumulated in a descriptive summary to give an overview of the *warning type* differences over all *scenarios*.

3. Results

3.1. Subjective ratings of the scenarios (situation criticality)

All results of the 2 × 8 × 5 mixed ANOVA of the subjectively rated situation criticality of each scenario for both within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type* are reported in Table 6. The analysis showed a significant interaction between the two factors *scenario* and *trial* as well as a significant main effect of the *scenario* and a marginally significant *trial* main effect. No further significant main effects or interactions between any factors were found. As Fig. 3 shows, scenario PS (pedestrian crossing on straight road) was the most critical, being rated *very high*. It was followed by scenario BI (bicyclist crossing at left turn) and the first trial of scenario PI (pedestrian crossing at left turn), both being rated *rather high* in situation criticality. Scenarios of *moderate* criticality were the second trial of PI, the scenarios BT (bicyclist crossing after right turn), LI (lead vehicle stopping at intersection) and OH (obstacle behind a hill) as well as the second trial of LS (lead vehicle braking on straight road). Of *rather low* criticality was the first trial of scenario LS and both trials of scenario OC (obstacle blocking road behind curve). The situation criticality changed about one scale point over the *trials*, while the effect direction differed with the scenario (see Fig. 3). The results of the multiple comparisons for the significant factor *scenario* are displayed in Table A1 in Appendix A. All further diagrams order the scenarios according to their described situation criticality.

3.2. Collisions

The GEE of the collision frequency (including all three main effects of the within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type*) showed two main effects, for the within-subjects factors *scenario* ($X^2_{(7)} = 118.76$, $p < .001$, $r = 0.35$) and *trial* ($X^2_{(1)} = 5.14$, $p = .023$, $r = 0.07$), but no main effect for the between-subjects factor *warning type* ($X^2_{(4)} = 5.92$, $p = .205$). Interactions could not be analyzed due to statistical constraints (see 2.6 Data analysis). Overall, the number of crashes was quite low with about 13%. A total of 120 collisions at 960 encounters of safety-critical objects was recorded. 5% less collisions occurred in the second trial compared to the first. In the most critically rated scenario PS almost half of all event encounters resulted in a collision with the pedestrian crossing the straight road. The second largest number of collisions, amounting to about a quarter of all encounters, occurred in scenario BI (bicyclist crossing at left turn),

Table 5
Number of data points per*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 $> 2.9\,s$ or $< 0.2\,s$).

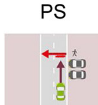
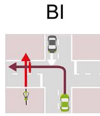
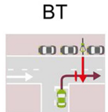
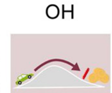
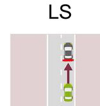
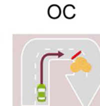
Scenario	PS	BI	PI	BT	LI	OH	LS	OC	
Brake reaction									Overall
Valid	120	96	91	69	32	111	116	105	740 (77.1%)
> 2.9 s / None	0	22	26	51	28	6	4	15	152 (15.8%)
< 0.2 s	0	2	3	0	60	3	0	0	68 (7.1%)

Table 6
ANOVA results for all interaction and main effects of the within-subjects factors *trial* (T) and *scenario* (S), and the between-subjects factor *warning type* (W) on the subjective ratings of the situation criticality (significant *p*-values in bold).

Situation criticality				
Effect	*F*	*df*	*p*	η^2
T	3.46	1,55	0.068	0.06
S	75.58	5.4,295.6	**< .0001**	0.58
W	1.09	4,55	0.371	0.07
T × S	2.97	5.4,295.6	**0.01**	0.05
T × W	1.11	4,55	0.361	0.75
S × W	0.57	21.5,295.6	0.936	0.04
T × S × W	0.87	21.5,295.6	0.639	0.06

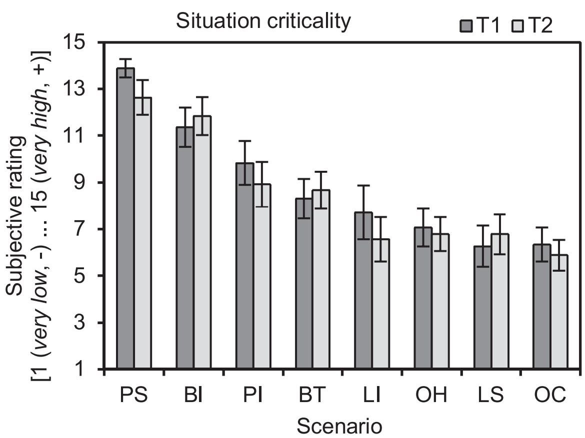


Fig. 3. Mean subjective ratings of the situation criticality (with 95% CI) per *trial* and *scenario*.

followed by the scenarios PI (pedestrian crossing at left turn) and LI (lead vehicle stopping at intersection) with a collision frequency of 12% each. No collisions were found in the scenarios BT (bicyclist crossing after T-section), OH and OC (obstacle behind hill and curve), and almost none in scenario LS (lead vehicle braking on straight road: 3%). These differences in the collision frequency between the scenarios are in line with the above described situation criticality ratings of the drivers (except for scenario LI).

3.3. Driving behavior (brake reaction time and brake maximum)

All results of the linear mixed model analysis of the brake reaction time and the brake maximum (including all factorial effects of both within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type*) are reported in Table 7. The analysis showed a significant interaction effect of *scenario* and *warning type* as well as significant main effects of all three factors on the brake reaction time. No further interactions became significant. Drivers initiated a 0.16 s earlier brake reaction in the second trial compared to the first trial (T1: $M = 1.20\,\text{s} \pm 0.05\,\text{s}$, $n = 374$; T2: $M = 1.04\,\text{s} \pm 0.04\,\text{s}$, $n = 366$). So the repeated exposure led to faster driver reactions, but this learning effect did not interact with the *scenario* or the *warning type* effect. The fastest brake reactions across all scenarios were found when a pedestrian crossed a straight road in scenario PS (see Fig. 4), which left the least amount of time to react (not accounting for scenario LI – lead vehicle stopping at intersection – in which more than half of the drivers initiated a brake reaction before the warning onset, see 2.6 Data analysis, leading to wide confidence intervals for the small amount of included participants). Scenario PS differed significantly from all other scenarios (exempt LI) in the shown brake reaction time according to post-hoc tests ($p \leq .001$). The results of all post-hoc pairwise comparisons of the brake reaction time and the brake maximum for the significant factor *scenario* can be found in Table A1 in Appendix A.

Table 7
Linear mixed model results for all interaction and main effects of the within-subjects factors *trial* (T) and *scenario* (S), and the between-subjects factor *warning type* (W) on the brake reaction time and brake maximum (significant *p*-values in bold).

	Brake reaction time			Brake maximum		
Effect	*F*	*df*	*p*	*F*	*df*	*p*
T	23.96	1,630	0.068	0	1,618	0.068
S	17.8	7,616	**< .0001**	84.71	7,611	**< .0001**
W	4.97	4,64	0.371	4.7	4,60	0.371
T × S	1.47	7,615	**0.01**	0.88	7,611	**0.01**
T × W	0.47	4,621	0.361	1.6	4,614	0.361
S × W	1.94	28,615	0.936	2.21	28,611	0.936
T × S × W	0.95	27,613	0.639	0.47	27,610	0.639

As Fig. 4 illustrates, warned drivers mostly had faster brake reactions than drivers without assistance (control: C), reaching significance in post-hoc pairwise comparisons for the significant factor *warning type* (C-RG: $p = .001$; C-RS: $p = .014$; C-AG: $p = .019$; C-AS: $p = .007$). The brake reaction time between the four driver groups who received a warning though did not differ significantly due to the *warning type* itself in post-hoc tests. Their efficacy and the degree of differentiation between the warning concepts depended on the *scenario*. As Fig. 4 shows, descriptively the attention specific (AS) and reaction generic (RG) warnings often led to the fastest reactions. While the brake reaction time over all warning concepts was quite comparable in the most critically rated scenario PS, AS warning was more beneficial in very and rather critical scenarios like BI and PI, and RG warning more in scenarios of moderate to rather low situation criticality like OH, LS or OC.

Similar to the brake reaction results, the mixed-model analysis for the brake maximum showed a significant interaction between the factors *scenario* and *warning type*. Both factors also led to significant main effects in the brake maximum, whereas contrary to the brake reaction results the factor *trial* did not (see Table 7). There were no further significant interactions.

As Fig. 5 illustrates, drivers' brake maximum varied widely over the *warning types*, but especially over the *scenarios*. While some scenarios prompted brake maxima within the upper third, other scenarios only induced slight braking within the lower third (for results of the multiple comparisons between the scenarios see Table A1 in Appendix A). As Fig. 5 shows, the RG (reaction generic) warning group mostly reached the highest value, aside from scenario LI with the lead vehicle stopping at an intersection (highest value from the only two includable data points in the control group) and BI (bicyclist crossing at left turn), in which the closely following AS (attention specific) warning group had the highest values instead. When comparing the *warning types* in post-hoc tests, only the RG warning differed significantly from other *warning types*, namely from the control group and the RS (reaction specific) warning group (RG-C: $p = .007$; RG-RS: $p = .001$; see Fig. 5).

3.4. Subjective ratings of the warnings (understandability and helpfulness)

All results of the 2 × 8 × 5 mixed ANOVA of the subjectively rated warning understandability and helpfulness for the within-subjects factors *trial* and *scenario*, and the between-subjects factor *warning type* are reported in Table 8. The analysis of the warning understandability showed a significant interaction effect of the factors *scenario* and *warning type*. Moreover, each of the three factors itself had a main effect on the warning understandability. No further interactions were found.

Drivers rated the warning concepts more understandable in the second trial than in the first (T1: $M = 9.8 \pm 0.4$; T2: $M = 10.5 \pm 0.3$), but both times the understandability was *rather high*. As Fig. 6 illustrates, the reaction generic (RG) and the attention specific (AS) warning were understood best in most of the scenarios. Moreover, post-hoc

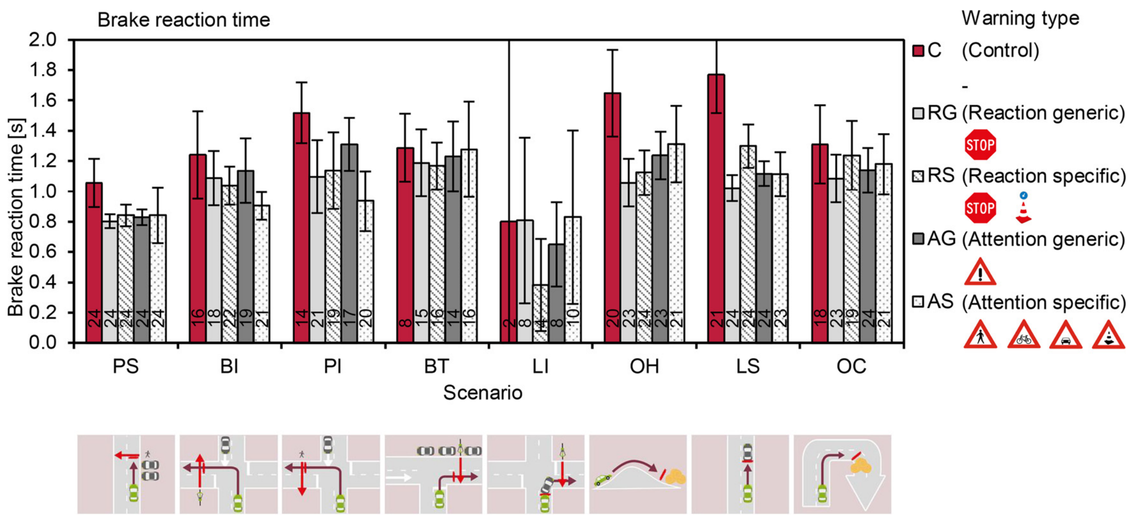


Fig. 4. Mean brake reaction time (with 95% CI) per *scenario* and *warning type* (*n* at the base of each bar).

pairwise comparisons for the *warning type* showed that the AS warning was understood significantly better than the reaction specific (RS) or attention generic (AG) warning (AS-RS and AS-AG: $p = .016$), while no significant differences were found for the RG warning (RG-RS and RG-AG: $p = .142$). Further pairwise comparisons for the factor *scenario* are reported in Table A1 in Appendix A. Mainly scenario LI (lead vehicle stopping at intersection) differed significantly from the other scenarios. Its quite low warning understandability rating though might go along with many drivers braking before warning onset and thus not understanding the need for a warning activation in general (as indicated in post-hoc interviews).

Regarding the warning helpfulness there was a significant main effect of the within-subjects factor *scenario* and a marginally significant interaction between the factors *trial* and *scenario*. No further main effects or interactions were found. Fig. 7 shows that the warning helpfulness was averagely rated *moderate* (8) to *rather high* (10) in all scenarios, except for scenario LI (lead vehicle stopping at intersection), in which the warning helpfulness was the lowest (6, *rather low* to 7, *moderate*) compared to all other scenarios (LI-PS: $p = .054$; LI-BI: $p = .027$; LI-PI: $p < .001$; LI-BT: $p < .001$; LI-OH: $p < .001$; LI-LS: $p = .111$; LI-OC: $p = .001$). This relates to the number of data points excluded due to drivers initiating a brake reaction before warning onset (being 50%, see 2.6 Data analysis). The *scenario* main effect might hence be strongly correlated to the low helpfulness in scenario LI. As can be seen in Fig. 7, except for the two obstacle scenarios (OH and OC), the warning helpfulness increased in all scenarios with time. Post-hoc driver interviews indicated that the warning in these specific scenarios was not always necessary as drivers sometimes recognized the safety-critical object before the warning was presented.

3.5. General results

Table 9 summarizes the results by reporting the mean of every measured parameter in each *scenario* as well as the most and least effective *warning types*. As illustrated, the subjectively rated situation criticality was significantly affected by the within-subjects factor *scenario*, which also interacted with the within-subjects factor *trial*. All scenarios actually differed from each other, allowing ordering them according to their situation criticality ratings. As Table 9 shows, scenario PS clearly bordered the situation criticality rating on the upper end ($M = 13$, *very high*) and scenario OC on the lower end ($M = 6$, *rather low*). While most scenarios were rated less critical when experienced again, this effect was inversed for both bicyclist scenarios (BI and BT) and LS (lead vehicle stopping on straight road).

As can be seen in Table 9, the total crash rate was quite low. It decreased significantly over time and differed significantly with the

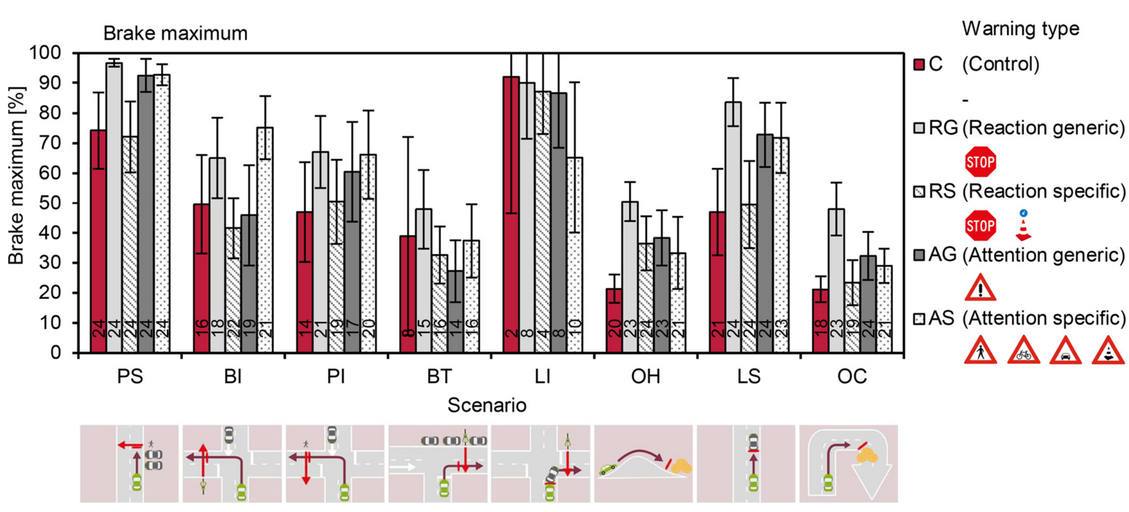


Fig. 5. Mean brake maximum (with 95% CI) per *scenario* and *warning type* (*n* at the base of each bar).

Table 8
ANOVA results for all interaction and main effects of the within-subjects factors *trial* (T) and *scenario* (S), and the between-subjects factor *warning type* (W) on the warning understandability and helpfulness (significant *p*-values in bold).

	Warning understandability				Warning helpfulness			
Effect	*F*	*df*	*p*	*r*	*F*	*df*	*p*	*r*
T	14.91	1,44	**< .0001**	0.25	2.33	1,44	1.34	0.05
S	6.67	5.0,222.0	**< .0001**	0.13	5.35	4.5,197.5	**< .0001**	0.11
W	5.32	3,44	**.003**	0.27	1.04	3,44	.384	0.07
T × S	0.75	7,308	.629	0.02	2.17	5.0,219.7	.058	0.05
T × W	0.53	3,44	.665	0.04	0.09	3,44	.964	0.01
S × W	5.84	15.1,222.0	**< .0001**	0.29	1.52	13.5,197.5	.110	0.09
T × S × W	0.98	21,308	.493	0.06	0.81	15.0,219.7	.666	0.05

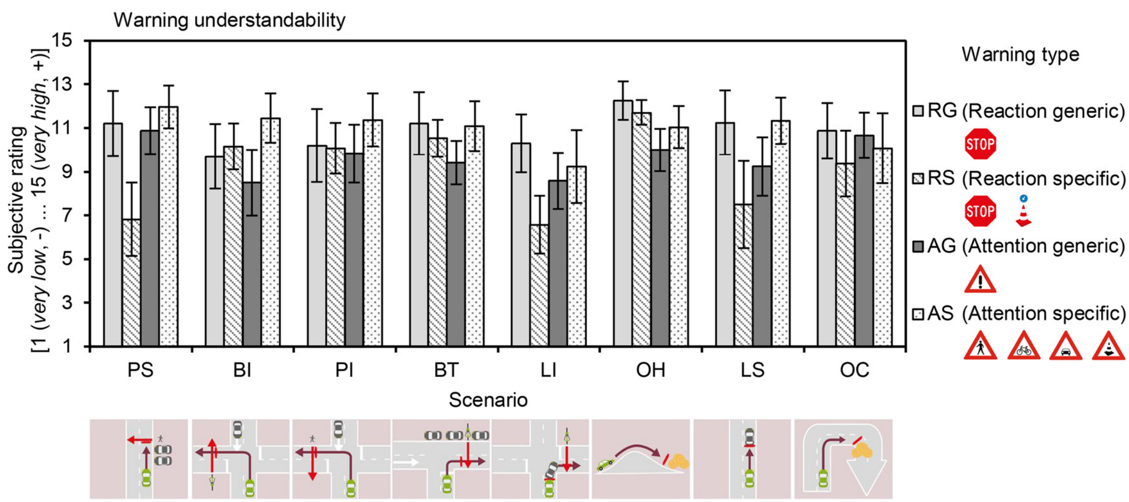


Fig. 6. Mean subjective ratings of the warning understandability (with 95% CI) per *scenario* and *warning type*.

factor *scenario*. The largest number of collisions was found in scenario PS (48%), about half as much in scenario BI (27%) and just a fourth of that in the scenarios PI and LI each (12%). No collisions were found in scenario BT and both obstacle scenarios (OH and OC), while 3% occurred in LS. The *warning type* did not affect the collision frequency. Nevertheless, Fig. 8 (left) illustrates that descriptively the control group (C) was involved in the largest number of collisions (17%) and the reaction generic (RG) warning group in the least (8%).

Besides the between-subjects factor *warning type* and the within-subjects factor *scenario* interacting significantly for the three parameters brake reaction time, brake maximum and the subjectively rated warning understandability, each of the two factors also had a significant main effect (see Table 9). Thus, there is no clear overall best *warning type* to be identified as the differences between the *warning types* varied with the *scenarios*. However, drivers in the control (C) group without warning support almost always showed slower, less strong brake reactions than warned drivers (brake reaction time: M_C = 1.4 s ± 0.1 s; brake maximum: M_C = 45% ± 6%). Only the reaction specific (RS) warning group achieved similarly low brake maxima (M_{RS} = 46% ± 5%, see Fig. 8, left). As Table 9 and Fig. 8 illustrate descriptively, the reaction generic (RG) and attention specific (AS) warnings led to the fastest and strongest brake reactions over all scenarios (brake reaction: M_{RG} = 1.03 s ± 0.06 s and M_{AS} = 1.05 s ± 0.08 s; brake maximum: M_{RG} = 68% ± 4% and M_{AS} = 60 ± 5%), while being understood best (both rated *rather high*, *M* = 11 ± 0.4). Moreover, there were many significant pairwise comparisons for the factor *scenario* in all three named parameters (see Table A1 in Appendix A). Scenario LI altogether differed clearly from most other scenarios.

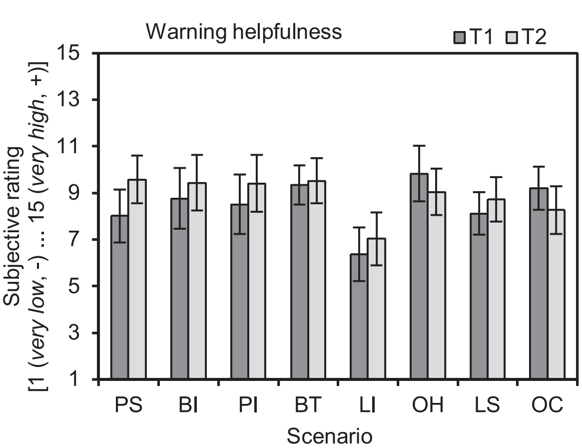
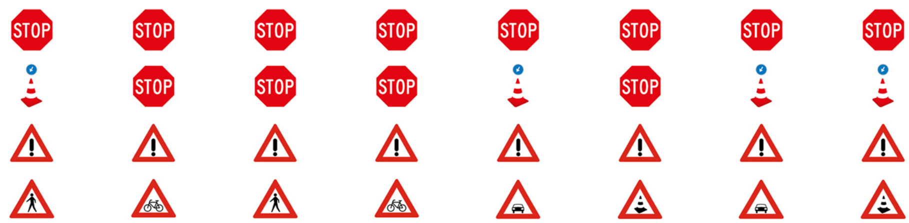
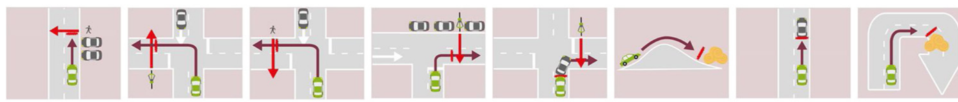


Fig. 7. Mean subjective ratings of the warning helpfulness per *trial* and *scenario* (with 95% CI).

Additionally, the within-subjects factor *trial* had a significant main effect on the brake reaction time and the subjectively rated warning understandability. Like the collision frequency, the brake reaction time decreased in the second trial, whereas the warning understandability increased with time. Similar to the situation criticality, the within-subjects factors *trial* and *scenario* interacted marginally for the subjectively rated warning helpfulness, with an additional significant main effect of the factor *scenario*. It increased towards the second trial in almost all scenarios, except for the obstacle scenarios. This might correlate with the fact that both scenarios were of *moderate* to *rather low* situation criticality (see Table 9). Additionally, all warnings were

Table 9
Overview of the significant effects of the factors *trial (T)*, *scenario (S)* and *warning type (W)* in the measured parameters (with overall means per *scenario* and descriptively most/least effective warning types by order, if *warning type* was significant).

Warning type	Control		-	-	-	-	-	-	-	-
	Reaction generic (RG)									
	Reaction specific (RS)									
	Attention generic (AG)									
	Attention specific (AS)									
Scenario			PS	BI	PI	BT	LI	OH	LS	OC
										
Measure	**Effect**	**Facet**								
Situation criticality	S, T × S	*M* [1-15]	13	12	9	8	7	7	7	6
Collisions	T (T1 > T2), S	*M* [%]	48	27	12	0	12	0	3	0
Brake reaction time	T (T1 > T2), S, W, S × W	*M* [s]	0.9	1.1	1.2	1.2	0.7	1.3	1.3	1.2
		Fastest	AS, RG, AG, RS	AS	AS	RS, RG, AG	RS	RG, RS	RG	RG, AG
		Slowest	C	C	C	C, AS	AS, C, RG	C	C	C
Brake maximum	S, W, S × W	*M* [%]	86	55	59	37	81	36	65	32
		Highest	RG	AS	RG, AS	RG	C, RG	RG	RG	RG
		Lowest	RS, C	RS	C	AG	AS	C	C, RS	C, RS
Warning under-standability	T (T1 < T2), S, W, S × W	*M* [1-15]	10	10	10	11	9	11	10	10
		Highest	AS	AS	AS	RG, AS, RS	RG	RG, RS	AS, RG	RG, AG
		Lowest	RS	AG	AG, RG, RS	AG	RS	AG	RS	RS
Warning helpfulness	S, T × S	*M* [1-15]	9	9	9	9	7	8	9	9

moderately helpful independent of the assigned warning group (see Fig. 8, right). A three-way interaction of all three factors was found nowhere.

4. Discussion

The present driving simulator study investigated how different concepts of a visual driver warning (*warning type*) influence objective variables such as collision frequency, brake reaction time and brake maximum as well as subjective variables like warning understandability and helpfulness in repeated *trials* of eight safety-critical situations (*scenario*). The aim of these driver warnings was to support drivers in various urban situations that might pose hazards to the traffic safety (accident prevention and mitigation). For example, it should help drivers to show a very fast and strong brake reaction in a highly critical situation of a pedestrian crossing the ego vehicle's path out of a sudden.

All scenarios differed clearly in the drivers' ratings of the situation criticality (ranging from *rather low* to *very high*), requiring different driver reactions for collision avoidance. Likewise, all other measured parameters (quantitative and qualitative) varied due to the factor

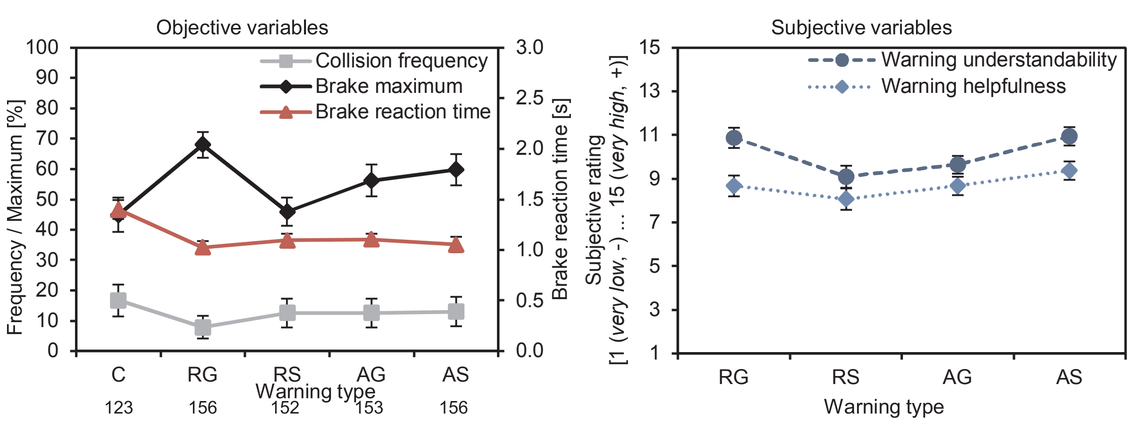


Fig. 8. Objective variables (*n* at the bottom, left) and subjective variables (right) per *warning type* (with 95% CI).

scenario (see Table 9). While the safety-critical situation in scenario PS (pedestrian crossing straight road) made emergency braking necessary, the same quick and strong brake reaction would have been inappropriate in scenario OC (obstacle behind curve), in which a gas pedal release or a moderate brake reaction was sufficient. Therefore, the scenarios established an appropriate framework to investigate the different strategies and specificities of the warning concepts (as varied by the *warning type*) and their general effectiveness. However, it should be noted that the used scenarios are not a representative sample of typical accident-prone urban scenarios, which is why the results cannot serve to estimate safety effects of such warning systems in real-world traffic. Nevertheless, they allow assessing whether certain warning systems are able to cover a wide and typical range of safety-critical situations requiring different driver reactions.

However, interpretations in scenario LI (lead vehicle stopping at intersection) have to be handled with care due to a quite high variance in the driving behavior within the scenario (especially right before hazard encounter). On the one hand, there were participants driving particularly carefully (e.g., with very low speeds and large safety distances), so that some situations did not become critical in the first place. On the other hand, a few drivers drove rather riskily in this scenario and reached a criticality and time frame in which the vehicle might take over control intervening for instance with automatic emergency braking (Muhrer et al., 2012). Nevertheless, such interventions were not focused here. The concerned warning concepts still surrendered the vehicle control to the drivers as that way false alarms might be more forgivable. However, interventions should be included when the present results are integrated in future multi-stage warning systems. Concluding, scenario LI would have to be adjusted for further evaluations, while the other seven scenarios could be well recommended for such purposes. Still, the variation within the individual scenarios due to naturally different driver behavior was a drawback that has to be acknowledged.

As expected, drivers significantly reacted slightly faster, avoided somewhat more collisions and understood the warning concepts a bit better with increasing experience over time, whereas the maximal applied brake force stayed unchanged over the two *trials*. However, in general the warning concepts seemed to be intuitively understandable from the start and did not need familiarization, except for when the reaction specific (RS) warning instead of the stop symbol displayed the “steer symbol”, a cone topped by an arrow pointing sideways (for evasive maneuvers in the scenarios PS, LI, LS – lead vehicle stopping on straight road – and OC). 42% of the drivers in the reaction specific (RS) warning group could not explain the meaning of the “steer symbol” with certainty or had wrong associations in post-hoc interviews (such as “steer symbol” for static obstacles, stop symbol for moving ones). Additionally, the RS warning resulted in rather low brake maxima compared to the other *warning types*. On the one hand, this makes sense as it was to elicit steering reactions rather than brake reactions. On the other hand, none but one of the drivers in the whole experiment (who was not even assigned to the RS warning group) actually showed an evasive maneuver, despite it being a valid alternative.

So the “steer symbol” should be redesigned and have a more action-prompting character to evaluate a RS warning approach including evasive maneuvers closer. For example, Maag et al. (2015) found more promising results with their “steer symbol” (depicting a road with lanes and a steering wheel topped with arrows in the HUD). Yet, in a study aimed at only evasive maneuvers drivers might have been generally more likely to react by steering than they normally would. Other studies showed that drivers universally tend to brake rather than steer in safety-critical situations (see Adams, 1994; Malaterre et al., 1988). Thus, prompting evasive maneuvers seems hard to achieve through visual warnings only. Haptic or multimodal signals or even automatic vehicle interventions might be better approaches to evasive maneuvers in a later warning stage before an imminent collision (Fricke et al., 2015; Maag et al., 2015; Schneider et al., 2015). On the other hand, the safety-critical situations themselves might have provided insufficient cues to induce steering responses. For example, scenario OC (obstacle blocking road behind curve) welcomed a steering reaction as there was no oncoming traffic, but the early warning onset might also have facilitated more familiar (or reliable) brake reactions. Besides, as mentioned before it was difficult to find generic warning symbols that elicit driver reactions, which is why the stop symbol was used to elicit a generic reaction in the reaction generic (RG) warning and a brake reaction in the reaction specific (RS) warning. Thus, the stop symbol in RG might not entirely be understood as a generic warning, but it was used in a generic way as it did not adapt and was displayed throughout every scenario.

Unfortunately, the collision frequency was not influenced significantly by the visual driver warnings. Descriptively, the reaction generic (RG) warning with the stop symbol though led to the least amount of collisions, while the control group without a warning had the most. In general, the crash rate was quite low, which also did not leave much variance to be explained. This could be due to the frequent encounter of hazards in the experiment. On the one hand, this allowed evaluating warning concepts in diverse situations (instead of just one use case) to further extend its applicability to various kinds of situations. On the other hand, this meant that drivers experienced critical incidents in a considerably higher frequency than in everyday traffic. Thus, they were probably more attentive and careful than they would normally be or even stressed, which might have affected the results. The fact that the study was situated in the laboratory environment of a driving simulator instead of in the field (as discussed in Lee et al., 2002a) might have also contributed to this. Whether a collision occurs highly depends on the dynamics of a vehicle (e.g., speed, lateral and longitudinal distances, steering angle) which are often not sufficiently represented in simulators. So collision frequencies measured in the simulator are limited in their external validity. However, the drivers' brake behavior is rather comparable to real driving and is thus considered a more reliable measure for generalizations to the real world (see Boda et al., 2018).

Moreover, drivers expected safety-critical situations to occur as they were instructed to rate the situation criticality. However, it was difficult to anticipate (especially in the first trial) what the actual safety-critical situations might look like and where they might appear as the situations were various and randomized in order. Nevertheless, the actual experience of collisions might still have influenced subjective ratings, such as concerning the situation criticality. Besides, driving simulator studies are quite complex and have to deal with simulation sickness, which is why some participants had to be substituted. Yet, the laboratory environment enabled better to control disturbing factors and trigger safety-critical events and warnings, especially without actually harming anyone. Still, it would be interesting to see whether similar effects could be found if the warning concepts were implemented in real traffic.

The results further showed that the drivers' brake reactions and the warning understandability (not its helpfulness) were significantly influenced by the *warning type* and its interaction with the *scenario*. All warning concepts were effective in reducing the brake reaction time significantly, despite it also significantly decreasing somewhat over time. The reaction generic (RG) warning with a stop symbol additionally increased the maximal applied brake force compared to no warning. The RG and the attention specific (AS) warning (with a warning triangle depicting the hazard) were rated highest on the warning understandability scale (both $M = 11$, *rather high*). Beyond that, the AS warning was significantly better understood than the reaction specific (RS) warning ($M = 9$, *moderate*), which alternated between a stop and a “steer symbol”, and the attention generic (AG) warning ($M = 10$, *rather high*) with an exclamation mark in a warning triangle. Overall, the warning understandability increased significantly towards the second *trial*.

Still, the efficacy of the different warning concepts clearly altered with the *scenario*. This is an important implication for the design of warnings as well as for the methodology in future research. It proved the assumption that common testing of driver assistance systems in a limited number or diversity of use cases is insufficient. Different driver responses were elicited by various combinations of scenarios and warnings. So one and the same *warning type* can lead to varied driving behavior and situation criticality ratings depending on the *scenario*. Yet, driver can also adapt their behavior to different warnings in the very same safety-critical situation. ADAS thus have to be tested in a wider manner.

Other implications concern the warning design. While the reaction generic (RG) and attention specific (AS) warnings often led to one of the fastest and strongest brake reactions, AS warning was somewhat better in rather critical scenarios and RG warning in lesser critical scenarios, respectively. However, the RG warning always led to one of the highest brake maxima by drivers in all scenarios (except for the conspicuous scenario LI). As both *warning types* though did not significantly differ from each other in any measured parameter, either one might be recommended as overall best warning concept. Yet, the AS warning might make comparatively greater demands on the quick identification of hazards (in terms of accuracy and latency) in order to display the correct object type within the warning triangle. This is still work in progress though. Detecting safety-critical objects, classifying them and especially predicting their future behavior, such as whether there is a tree swaying in the wind or a pedestrian bending forward in an attempt to cross the road, is still a challenge to current technologies and system developers (see Cordts et al., 2017; Diederichs et al., 2018; Schmidt and Färber, 2009). An incorrectly displayed warning symbol can be quite distracting and cause acceptance problems (Abe and Richardson, 2006; Horowitz and Dingus, 1992; Naujoks et al., 2016). Since such false alarms might be more likely with the AS warning, the RG warning might be preferable due to its generic display (especially in time-critical situations). In general, false alarms were not part of this study, which should be kept in mind regarding the results. Drivers always associated an actual hazard to the situations. This limits the ecological validity of the study and should thus be included in a next step.

A lot of drivers also reacted before the warning was triggered or drove in a way that hindered some situations from becoming critical in the planned way so that the number of data points included per scenario and warning group vary more or less. This should be taken into account for result interpretation. Furthermore, the warning system (with its different warning strategies and specificities) should be tested with other driver groups like older, experienced or impaired drivers. On the one hand, driving related skills like regarding attention allocation, information perception, processing and action execution can deteriorate with increasing age and impairments (e.g., Caird et al., 2007; Piersma, 2018; Rackoff, 1974; Schlag, 1993; Yan et al., 2007). On the other hand, driving experience can improve drivers' hazard perception and thus their crash involvement (Borowsky and Oron-Gilad, 2013; Borowsky et al., 2009; Malone and Brünken, 2016; Pradhan et al., 2009). Hence, drivers might need different support (by warnings) in various hazardous situations depending on factors such as age, fitness to drive or driving experience.

Despite the named limitations, the results of the study contribute to a wider knowledge of how to design driver warnings and how drivers react when confronted with different kinds of hazards. As there was a positive effect of the developed assistance (warnings displayed in the HUD) on the driving behavior (faster and stronger brake reactions), the severity of possible collisions could be reduced. The reaction generic (RG) stop symbol and the attention specific (AS) hazard depiction within a warning triangle were most effective in eliciting faster and stronger driver reactions. Clear differences between the individual warning concepts though could not be found throughout all measured parameters. Descriptively, the RG warning led to the least collisions, the RG and AS warning to the fastest brake reactions and RG to the strongest ones, while both were understood rather well compared to the other warning groups. In general, the reaction generic stop symbol warning seems to be optimal considering its generic use allows triggering it even when the type of safety-critical object is not yet clearly identifiable. However, such an extreme reaction as elicited by the RG warning might surprise following traffic, since none of the usual cues to anticipate such driving behavior like turning indications are present in the case of a collision warning. Thus, the following drivers might not be ready to intervene abruptly, which is why they might not react in time and crash into the previously warned lead vehicle (see Baldock et al., 2005; Muhrer and Vollrath, 2010; Najm et al., 1994). Moreover, drivers could feel stressed and annoyed by a reaction demand deemed as too intrusive regarding a situation of lower criticality. Therefore, a universal warning type does not seem feasible.

It should be considered to implement the findings of this study into a multi-stage warning system, which displays a stop symbol as reaction-oriented generic warning in very critical situations (at a late stage), but a different *warning type* in less critical situations (at an earlier stage) to prevent them from becoming more critical (Werneke et al., 2014; Winkler et al., 2016; Winkler et al., 2018a). As in less critical situations drivers need to be more attentive and can take more time to react, an attention-oriented warning might be useful. Choosing the generic version of the attention-oriented warning strategy (exclamation mark within warning triangle) might be preferred as in the less critical situations it leads to similar driver reactions than its specific counterpart, but would allow the warning system more flexibility as it can be used for many different use cases. Furthermore, generic warnings forgive errors in object detection and can thus reduce the potential risk of false alarms. Since multi-modal warnings might be even more effective to warn drivers (see Kramer et al., 2007), especially in very critical situations, a further modality could be implemented in a next research step. For example, the stop symbol as reaction generic visual warning in more critical situations or later warning stages (compared to less critical situations or earlier warning stages) could be accompanied by an acoustic signal in order to alert drivers stronger to an increased urgency of a situation. Besides, this could support drivers in differentiating better between both warning stages and even activate distracted drivers sufficiently, which might be engaged in a secondary task and thus have their gaze directed away from the road. In any case combining some of the symbols in a multi-stage warning system should be further investigated, as well as the case of false alarms or imperfect warnings.

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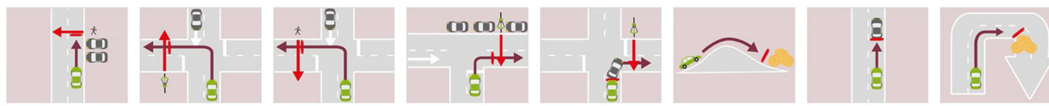
Appendix A

The post-hoc results of the multiple pairwise comparisons within the significant factor *scenario* for the situation criticality, the brake reaction time, brake maximum and the warning understandability can be found in Table A1 of Appendix A. Bonferroni-corrected *p*-values are reported.

Table A1
Multiple pairwise comparison results for the significant factor *scenario* (significant *p*-values in bold).



Measure	Scenario	PS	BI	PI	BT	LI	OH	LS	OC
Situation criticality	PS	-	**.001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	BI	**<.0001**	-	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	PI	**<.0001**	**<.0001**	-	1.000	**.004**	**<.0001**	**<.0001**	**<.0001**
	BT	**<.0001**	**<.0001**	1.000	-	.119	**<.0001**	**<.0001**	**<.0001**
	LI	**<.0001**	**<.0001**	**.004**	.119	-	1.000	1.000	1.000
	OH	**<.0001**	**<.0001**	**<.0001**	**<.0001**	1.000	-	1.000	.347
	LS	**<.0001**	**<.0001**	**<.0001**	**<.0001**	1.000	1.000	-	1.000
	OC	**<.0001**	**<.0001**	**<.0001**	**<.0001**	1.000	.347	1.000	-
Brake reaction time	PS	-	**<.0001**	**<.0001**	**<.0001**	1.000	**<.0001**	**<.0001**	**<.0001**
	BI	**<.0001**	-	.629	.233	**.003**	**.035**	**.038**	1.000
	PI	**<.0001**	.629	-	1.000	**<.0001**	1.000	1.000	1.000
	BT	**<.0001**	.233	1.000	-	**<.0001**	1.000	1.000	1.000
	LI	1.000	**.003**	**<.0001**	**<.0001**	-	**<.0001**	**<.0001**	**<.0001**
	OH	**<.0001**	**.035**	1.000	1.000	**<.0001**	-	1.000	1.000
	LS	**<.0001**	**.038**	1.000	1.000	**<.0001**	1.000	-	1.000
	OC	**<.0001**	1.000	1.000	1.000	**<.0001**	1.000	1.000	-
Brake maximum	PS	-	**<.0001**	**<.0001**	**<.0001**	1.000	**<.0001**	**<.0001**	**<.0001**
	BI	**<.0001**	-	1.000	**<.0001**	**<.0001**	**<.0001**	**.033**	**<.0001**
	PI	**<.0001**	1.000	-	**<.0001**	**<.0001**	**<.0001**	.937	**<.0001**
	BT	**<.0001**	**<.0001**	**<.0001**	-	.000	1.000	**<.0001**	1.000
	LI	1.000	**<.0001**	**<.0001**	**<.0001**	-	**<.0001**	**.042**	**<.0001**
	OH	**<.0001**	**<.0001**	**<.0001**	1.000	**<.0001**	-	**<.0001**	1.000
	LS	**<.0001**	**.033**	.937	**<.0001**	**.042**	**<.0001**	-	**<.0001**
	OC	**<.0001**	**<.0001**	**<.0001**	1.000	**<.0001**	1.000	**<.0001**	-
Warning understandability	PS	-	1.000	1.000	1.000	**.017**	.591	1.000	1.000
	BI	1.000	-	1.000	.073	.480	**.014**	1.000	1.000
	PI	1.000	1.000	-	1.000	**.035**	.313	1.000	1.000
	BT	1.000	.073	1.000	-	**.001**	1.000	1.000	1.000
	LI	**.017**	.480	**.035**	**.001**	-	**<.0001**	.580	**.002**
	OH	.591	**.014**	.313	1.000	**<.0001**	-	**.029**	1.000
	LS	1.000	1.000	1.000	1.000	.580	**.029**	-	1.000
	OC	1.000	1.000	1.000	1.000	**.002**	1.000	1.000	-

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