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Situational influences on response time and maneuver choice: Development of time-critical scenarios

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ABSTRACT

Findings concerning drivers' response times to sudden events vary considerably across studies due to different experimental setups and situational characteristics, such as expectancy of an event and urgency to react. While response times are widely reported in the literature, understanding of drivers' choice of maneuvers in time-critical situations is limited. Standardized test scenarios could enhance the comparability of studies and help in attaining a better understanding of driver behavior in these situations.

In an effort to achieve these improvements, three driving simulator studies ($N = 131$) were conducted to investigate drivers' response time and maneuver choice under a range of situational conditions. Each study took place in a specific environmental setting (urban, rural, and highway) and incorporated one unexpected and 12 subsequent events (increased expectancy). Four different time-critical scenarios were used to evoke different driver responses. In three scenarios, obstacles suddenly entered the roadway (braking, steering, or both possible). A fourth scenario comprised the sudden braking of a leading vehicle (only braking possible). Half of the drivers performed a cognitive secondary task. To validate the findings, results from an additional field test ($N = 14$) were compared to the results from the simulated urban environment.

As expected, response choice was influenced by scenario characteristics (available braking distance and room for evasive maneuvers). Braking maneuvers were more frequent in settings with lower speed limits (urban) while steering maneuvers were found at higher speed limits (highway). Responses to suddenly appearing obstacles were fastest in the urban setting at 540–680 ms; these responses were 200–300 ms slower in the rural and highway settings. Response times increased by 100–200 ms when drivers responded to braking leading vehicles rather than obstacles. Braking responses were 200–350 ms slower and steering responses were 90–200 ms slower when drivers responded to an unexpected event rather than subsequent events. The cognitive secondary task had no significant effect. The simulated environment and the field test produced comparable response behavior.

The current study provides reference numbers that help to establish a set of standardized test scenarios for future studies. On basis of this study, nine scenarios are recommended for the context of time-critical crash avoidance maneuvers. Such standardized test scenarios could improve the comparability of future studies on response time and maneuver choice.

1. Introduction

1.1. Driving performance and response times

Driver errors are one of the most frequent causes of crashes (e.g., Vollrath, 2010). When considering driver safety and crash prevention, one of the most important aims is to improve the driver's behavior. Improvements include preventing critical situations by assisting drivers in behaving adequately before a situation becomes dangerous. Even more importantly, driver assistance systems, such as a forward collision warning, help drivers avoid crashes in a situation that has become critical. To evaluate the effectiveness of such systems in a critical situation, a measure of driving performance is needed.

Overall, driving performance can be seen as a general term for how effectively a driver's behavior matches situational requirements (e.g., Fuller, 2005). As Dunn et al's. (2014) crash trifecta concept indicates, crashes require the simultaneous presence of the following factors: (1) unsafe pre-incident behavior, (2) transient driver inattention, and (3) an unexpected traffic event. The final element requires a fast and adequate response to avoid a crash. An essential measure of driver behavior in these critical situations is response time: the time that elapses between the start of the unexpected traffic event to the actual

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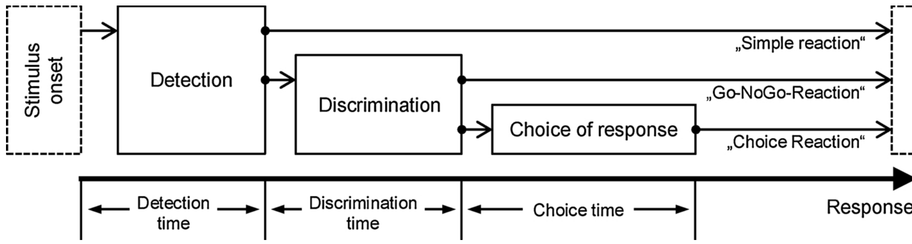

Fig. 1. The authors' visualization of the response process according to the stages proposed by Donders (1969).

adaption of the driving behavior. Driver assistance systems should help drivers to respond adequately (e.g. steering instead of braking) and as quickly as possible. A human factors evaluation of these systems should measure reaction type and response time.

A driver's response includes multiple stages (e.g., Boff and Lincoln, 1988). To respond to a time-critical event, a driver needs to detect relevant cues in the environment, distinguish safety-relevant cues from irrelevant cues in the ongoing situation, choose an appropriate maneuver, and execute on this choice. Early laboratory research on response times has identified several mental processes (e.g., Donders, 1969). As Fig. 1 illustrates, the stages of detection, discrimination, and response choice can be examined using different reaction time tasks. Donders (1969) described a method to estimate the duration of the single stages based on the assumption that these stages are independent of each other. For example, the discrimination time can be estimated by subtracting the response times for a simple response task from those for a similar Go-NoGo task (see Fig. 1). This subtraction method is similar to a baseline correction and is also used in other fields of research such as functional neuroimaging.

While other methods have been proposed (see Sternberg, 1969) and evidence of the validity of the independence assumption is mixed (see Miller and Low, 2001; Danek and Mordkoff, 2011), Donders' (1969) early work illustrates that even if the motor response (e.g., button press) and target stimuli are held constant, due to different cognitive processes, the actual onset of an observable behavioral response varies depending on the task in question.

1.2. Response times and situational factors

Returning to response times in traffic, a large body of literature examines the speed at which drivers respond to various traffic situations (reviews given by Green, 2000; Sohn and Stepleman, 1998; Young and Stanton, 2007). Average braking response times range from 0.4 s to 2.5 s. In some situations, response times have been found to be as long as 4.1 s (Adell et al., 2011). In his review of 40 studies on braking response times, Green (2000) found that response times varied considerably due to the different experimental setups of the studies and variations in the factors such as expectancy, urgency of the situation, cognitive load, and age and gender of the driver. The most important factor was expectancy, as in expected situations, response times were around 0.7 s. In unexpected but common situations, response times were around 1.25 s and in surprising situations (unexpected and uncommon) response times were around 1.5 s (Green, 2000).

Summala (2000) has criticized these values because of the aggregation of situations with different urgencies. According to Summala (2000) drivers want to hold a constant speed as long as possible, and they decelerate only if required by a situation. This effect would result in a biased estimation of drivers' ability to react to critical events if the critical events were not *time-critical* enough to require a fast response. The aggregation of different situations raises the question of whether the response times found by Green (2000) are estimates of how fast drivers *can* possibly respond or of how fast drivers *prefer* to respond considering the perceived requirements of a situation. To compare reaction times in critical situations, the situation characteristics may be the most prominent influencing factors.

Naturally, when evaluating a driver assistance system to determine whether it improves response times, it is sufficient to compare use and non-use of the system in identical test situations, e.g. by means of a driving simulator and a between-subjects design. However, to create or select test situations and estimate the generalizability of the findings, it is beneficial to know the extent to which situational factors influence response times. With this need in mind, the first aim of the current study was to examine the influence of basic situational factors such as road type and typical driving speed on the road.

1.3. Beyond response times: maneuver choice

While not reported as frequently as response times, maneuver choice is also a relevant feature of driver behavior. How fast a driver must react in a specific situation to avoid a collision can be easily determined by the basic parameters of the situation, including distance to the collision object, current speed, and anticipated deceleration rate. Whether a chosen response is the most appropriate for a situation is a more sophisticated question.

A review of crash avoidance strategies (Adams, 1994) revealed that in critical situations, drivers tended to choose braking maneuvers (39–91%) more often than steering maneuvers (9–24%). However, steering maneuvers tended to have higher success rates in terms of avoiding crashes and were effective even when the distance to an obstacle was very short. A crash analysis conducted by Ferrandez, Fleury, and Lepesant (1984, cited after Malaterre et al., 1988) found that in 31 out of 72 cases, a crash could have been avoided if the driver had chosen an appropriate maneuver. In two thirds of the cases, a steering maneuver would have been the appropriate choice. Using videos of critical situations, Malaterre et al. (1988) asked 12 subjects to indicate what maneuver they would have selected in a given situation and the reason for the choice. The results indicated that drivers tended to choose sideways maneuvers more frequently when (1) the distance to the obstacle was short; (2) the driver was certain of the obstacle's trajectory; and (3) visibility was strong. Since the answers did not match data found in crash analyses, the authors suggested that in actual critical situations, drivers do not rely on refined perceptual judgments and tend to follow simplified strategies.

Crash analyses have also revealed that drivers often fail to execute crash avoidance maneuvers (Kaplan and Prato, 2012, 2015; Harb et al., 2009). For example, in a study by Kaplan and Prato (2012), a steering maneuver that would have resulted in lower crash severity was performed only in 13% of the cases. While this finding seems alarming, it must be stated that the data was naturally biased towards unsuccessful crash avoidance behavior, since the studies only analyzed police-reported crash data and did not consider successful avoidance maneuvers in near-crash situations. However, the drivers' tendency to brake was also found in naturalistic driving (Dozza, 2013). In 66% of 493 near-crash events, the driver chose a braking maneuver; steering maneuvers were chosen in about 25% of the cases.

Overall, it seems that choosing the adequate response in critical situations may be even more important than responding as quickly as possible. Similar to the large range of response times between studies, significant variations were also found in response type. These variations may largely be due to specific characteristics of the critical situations examined. After reviewing the literature, it is difficult to conclude which of these factors are relevant to safety-critical behavior and in what ways. Knowing these influences is beneficial for the design of studies that evaluate driver assistance systems that may aim to induce a certain driver response such as emergency braking.

1.4. Aim of the current study

The current study investigated the influence of a range of situational factors on drivers' response time and maneuver choice in order to answer the question of what a relevant set of test situations might be. Put differently, the study sought to answer the question: What is the minimum set of situational factors a researcher should consider when investigating a specific research question about response times or maneuver choice? Answering this question would help in identifying relevant scenarios with which to answer the research question. Additionally, determining the necessary number of situational factors would help in establishing a balance between different methodological priorities in the experimental design.

To gain insight into possible relevant test scenarios a series of three experiments were run in a driving simulator. The study manipulated the global and situational characteristics of the environment as well as expectancy of an event and driver distraction. Time-critical situations were employed to create a strong need to react urgently. Global and situational characteristics of the scenarios were varied to (1) cover a wide range of conditions and (2) create situations that evoked specific driver responses. For these reasons, each of the three simulator studies focused on one of three environmental settings: urban road, rural road, and highway. Furthermore, the critical situations in each setting were designed to require a certain response from the driver – braking, steering, or a combination of both – to successfully avoid a collision. Since the majority of studies focus on response times only, the current study also emphasized response choice to gain deeper insight into the behavioral patterns that emerge in these critical situations. The experimental conditions of all studies should be comparable in order to establish a set of standardized scenarios and create sources of reference for future research. To further validate the findings of the driving simulator the current study incorporated an additional field test and the results were compared to the simulated urban environment.

1.5. Maneuver choice and situational factors

Most relevant to the current study are situations in which a driver's response time and maneuver choice are essential to avoiding a collision. These factors are crucial when an obstacle suddenly enters a vehicle's path or another driver abruptly changes his or her movement. Typical examples are pedestrians running onto the road and the sudden braking of a leading vehicle. These situations require an immediate response from drivers. Drivers can take two possible actions to avoid a collision: reducing their velocity by braking and changing their course by steering. As previously mentioned, drivers perform braking maneuvers more frequently than steering maneuvers. The scenarios in this study were designed to increase the likelihood of the respective maneuvers in order to investigate both response types.

The appropriateness of a response mainly depends on braking distance and amount of space in which to bypass an obstacle. In a driving simulator, both parameters can easily be manipulated. Restricting either braking distance or bypassing space, encourages drivers to conduct steering or braking maneuvers, respectively. If neither restriction is imposed, the driver is free to choose an appropriate action or combine both maneuvers. Following this idea, three basic scenarios were utilized in this study. In the braking scenario ("B"), drivers had no chance to swerve left or right and instead had to brake immediately to avoid a collision. In the steering scenario ("S"), the obstacle was too close to avoid a collision by braking. Drivers had to use the available lateral room to execute a swerving maneuver to avoid the collision. The third scenario ("BS") offered enough space to avoid the collision by either braking or swerving. A car following scenario was also implemented to compare responses elicited by a sudden new stimulus (object entering the road) to those elicited by an abrupt change in the existing stimulus (speed change of the leading vehicle). In this fourth scenario ("LV"), a leading vehicle suddenly decelerated to a full stop. As in the braking scenario, drivers had to brake immediately to avoid a collision because no space was available for bypassing the leading vehicle.

2. Method

2.1. Design

As described in the previous section, different scenarios were used to investigate specific driver responses. In addition to manipulating these situational factors, the study varied the global context of the driving task. This was done in three separate experiments, each of which utilized a different environmental setting, including driving in an urban area, on a rural road, and on a highway.

To estimate the range of response times in relation to driver expectancy, each participant drove the scenarios multiple times. This repetition made it possible to determine whether drivers react faster and can more effectively adjust their responses to the situation when they are aware of potentially dangerous events. The first scenario was implemented in a separate run and randomly selected from the three basic scenarios (B, BS, and S). In a second run, all four scenarios (including LV) were presented three more times in random order.

Half of the participants were introduced to a secondary task during the first run to assess the effects of cognitive load on response time and maneuver choice. To summarize, each participant drove one of the three basic scenarios either with or without the secondary task before driving all four scenarios three more times without the secondary task. This procedure was executed identically in all three environmental settings. The experimental design and sample sizes are presented in Fig. 2.

In addition to the three simulator studies, a field study was conducted. The setup was comparable to the urban setting and is described in section *2.8 Field test*.

2.2. Participants

Participants were recruited mainly through a student email distribution list and a database of former participants who volunteered to stay informed about upcoming studies. Since the study focused on environmental factors instead of interpersonal differences, the sample was a priori chosen to be homogenous regarding age. To be included, participants had to possess a driver's license and be between 20 and 40 years old. Participation was voluntary and participants were paid €40. Undergraduate students of psychology at Technische Universität Braunschweig had the option to earn hourly credits (a total of 20 h is required by the curriculum) instead of monetary compensation.

In total, 51 people participated in the first experiment (urban road). Five people dropped out due to simulator sickness. Only the data collected from the remaining 46 people was used in the analysis. The second experiment (rural road) included 42 participants, and the third experiment (highway) included 43. In the latter two settings, all participants completed the whole experiment. All three samples were similar in age, gender, and driving experience. Age ranged from 20 to 40 years, and the average ages were $M = 26.0$ years (Exp. 1; $SD = 4.7$ years), 26.9 years (Exp. 2; $SD = 5.7$ years) and 25.4 years (Exp. 3; $SD = 5.2$ years). Participants had held their driver's licenses for $M = 6.4$ years (Exp. 3; $SD = 4.8$ years) to $M = 8.3$ years (Exp. 1; $SD = 4.4$ years). Between 41% (Exp. 1) and 56% (Exp. 3) of the participants were female. About half of the participants drove up to

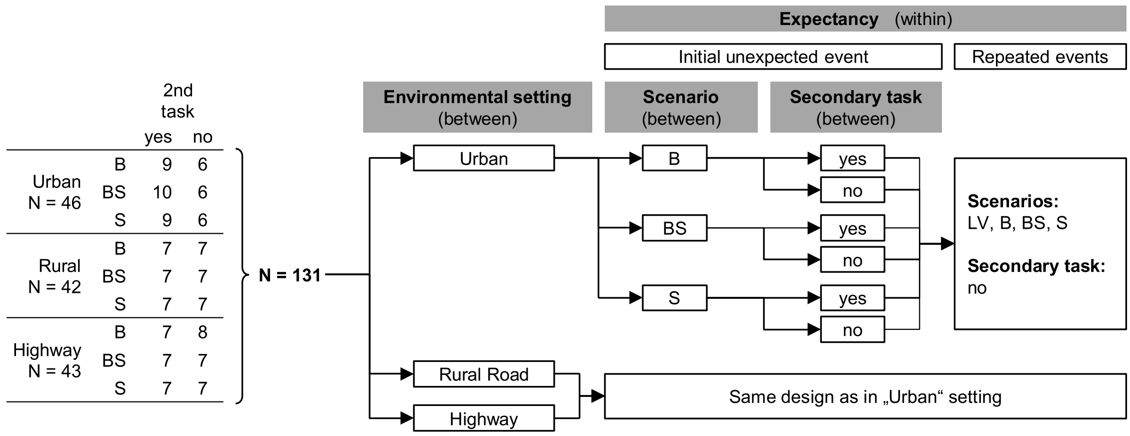

Fig. 2. Sample sizes and experimental design for the three simulator studies (urban, rural, and highway). Each participant drove one of the three basic scenarios (B, BS, and S) either with or without a secondary task before driving all four scenarios (including LV) three more times without a secondary task.

3,000 km per year. Only 4–7% drove more than 20,000 km per year.

2.3. Driving simulator

All three simulator experiments were conducted at the Department of Engineering and Traffic Psychology at the Technische Universität Braunschweig. SILAB 3.0 software was used to run a fixed base driving simulator (Krüger et al., 2005; see www.wivw.de). The mockup consisted of two seats, a steering wheel, and pedals. Separate displays were used to simulate mirrors and the speedometer. Three LCD projectors (1,400 × 1,050 pixels) presented the simulated environment onto three screens (each 2 × 2 m) covering a field of view of approximately 180°. Sound was played through stereo speakers. The experimenter could monitor the test drives on six computer screens in an adjacent room and communicate with participants over a microphone. Data including steering wheel angle, pedal position, current speed, and acceleration were recorded at a rate of 100 Hz.

2.4. Test track

The main challenge was to ensure that the critical events in the experiments were comparable. Across all three experiments, the main difference was speed limit, as the urban road setting included a speed limit of 50 km/h, the rural road limit was 100 km/h, and the highway limit was 130 km/h. Naturally, other factors such as number of objects, traffic density, and number of lanes also differed across the experiments, as the simulated environments were designed to be as realistic as possible.

The urban environment was the most complex setting in terms of visuals, as it included relatively high traffic density, crossroads, one-way roads, and many roadside objects, such as houses, parked cars, pedestrians, trees, and street lights. Driving on the rural road was more monotonous, and other road users were less important. The surrounding environment consisted of farming areas, woods, and small groups of houses. Randomly generated traffic drove in the oncoming lane (4–12 vehicles per minute) and other cars overtook the driver at irregular intervals. This setting was similar in the highway environment that featured four lanes moving in one direction, including an emergency lane. The width of the lanes in this setting was 3.75 m, while the lanes were 3.5 m wide in the rural and urban conditions. The oncoming lanes were separated from the forward-moving lanes by guardrails and hedgerows. In all three experiments, the participants were instructed to remain in the right lane. In the highway condition, participants were instructed to overtake slower cars in the right lane in order to maintain a speed of 130 km/h and return to the right lane afterward. Fig. 3 presents screenshots of the driving environment.

2.5. Critical events

The critical events were designed to require an immediate response from drivers. This goal was achieved using calculations based on stopping distance and response time data from pilot experiments. Fig. 4 schematically compares all four scenarios from the three experiments. Different strategies were used to elicit either a braking or steering response.

In the urban environment, participants drove along a straight one-way road that was blocked by parked cars on both roadsides or only one, depending on the scenario (B and LV vs. S and BS). When the driver reached a certain point, a previously hidden pedestrian crossed the road from the left or right side at a speed of 2 m/s. To minimize potential bias, the direction of the pedestrian was balanced, and the sequence of left and right crossings was randomized. According to the scenario, the distance at which the pedestrian was triggered was set at 20 m (scenario S), 23 m (scenario BS), or 25 m (scenario B). In the car following scenario (LV) a leading vehicle slowly reduced its velocity to reach a critical distance of 18 m from the driver's car and then suddenly braked to a full stop at a deceleration rate of $-9\,m/s^2$. The brake lights turned on but were far less prominent than the crossing pedestrian. However, the urgency was as high as in scenario B. All timings were based on pilot experiments and were chosen to require an immediate response while also being manageable for the driver.

In the rural and highway settings, no pedestrians were included in scenarios B, BS, and S. Instead, the driver had to respond to a vehicle that appeared suddenly (i.e. popped up) in his or her own lane. This represented a salient yet unpredictable event and was compared to scenario LV in which – similar to the urban setting – a previously present leading vehicle in front of the driver suddenly braked.

Space for bypassing the vehicle was restricted by guardrails and oncoming traffic (scenarios B and LV) in the rural setting; scenarios S and BS had no such restrictions. In the highway condition, participants drove in the right lane in scenarios S and BS and could use the middle and emergency lanes to bypass the leading vehicle. In scenarios B and LV, drivers had to overtake slower moving cars in the right lane. While driving in the middle lane, drivers were overtaken by cars in the left lane. Moving cars blocked both sides, and no space was available on either side to bypass the vehicle in front (Fig. 4).

Regarding distance to the critical object, drivers did not always follow the speed limit in the first experiment (urban setting), which might influence the criticality of the situation. To take this variation into account, the distances in the rural and highway settings were calculated for each event based on the driver's actual speed. The distances were determined by the braking distance (calculated using actual speed and an assumed deceleration of $-9\,m/s^2$) and an additional travel distance (calculated using the actual speed and response time).

Fig. 3. Screenshots taken from the urban (left) and highway (right) environments. The rural and highway environments had similar appearances (see text).

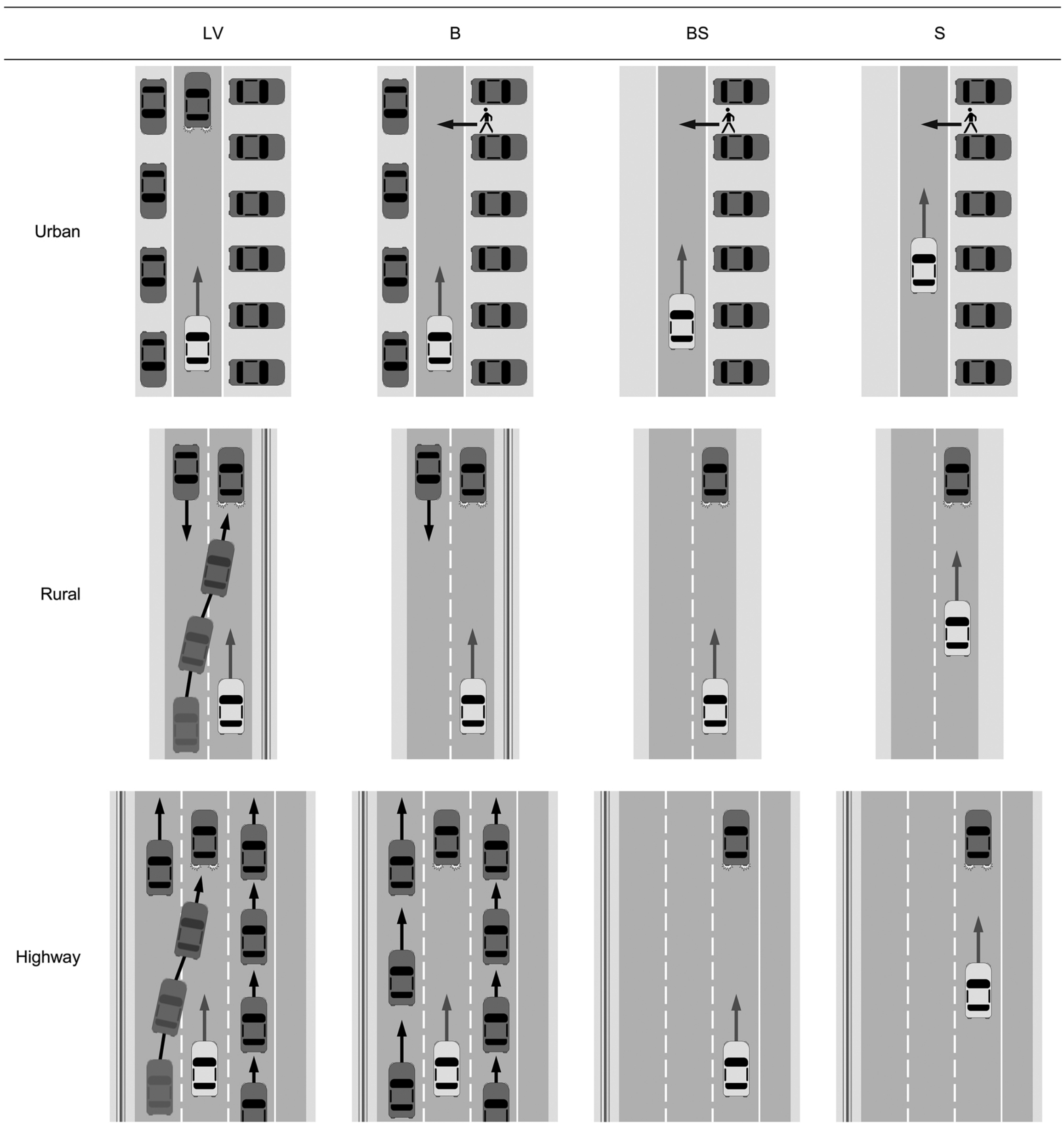

Fig. 4. Setup of the four scenarios in the three environmental settings. Distances are not represented to scale.

Depending on the scenario, the available response time was designated as either 1 s (scenarios B, BS, and LV) or 0.5 s (scenario S) in order to vary the feasibility of a braking maneuver. For example, unless a driver braked within 0.5 s, it was not possible to avoid a collision in scenario S. The response time values were based on data from the first experiment and pilot experiments conducted on the rural and highway tracks. When participants drove at the instructed speeds of 100 km/h and 130 km/h, respectively, the distances to the critical objects were around

71 m (rural: scenarios B, BS, and LV), 57 m (rural: scenario S), 109 m (highway: scenarios B, BS, and LV), and 91 m (highway: scenario S). In scenarios B, BS, and S, the critical vehicle appeared at a defined location as soon as the distance from the driver's vehicle to that location fell below the calculated critical distance. In scenario LV, the driver was overtaken by another car. After this car passed and returned to the right lane, the distance to this now leading vehicle steadily increased, due to its higher speed. Eventually, when the distance to the leading vehicle was equal to the calculated critical distance, the leading vehicle braked to a full stop (Fig. 4).

2.6. Secondary task

Half of the participants were randomly assigned to a secondary task during the first drive in order to investigate whether increased workload resulted in less appropriate or slower responses. To isolate the potential effects from visual distraction, a cognitive task was chosen. This way, the distracted drivers had the chance to visually detect the obstacle as quickly as the undistracted drivers. Participants in the secondary task condition were instructed to count backward aloud from a given number in increments of seven, similar to the serial sevens task (Hayman, 1942). The start number was written on road signs on the side of the track. Participants encountered the first road sign after 3 min of driving. To remind the participants of the task, additional signs with new numbers were displayed in intervals of 2–3 min. The critical event was placed in between these intervals to prevent interference from a potential visual distraction. Participants were instructed to perform the task until the end of the drive.

2.7. Procedure

Participants were informed about the general procedure of the experiment (training session, driving task, and duration of the experiment) and instructed to behave as they would in a real traffic situation with regard to the traffic regulations. However, participants were not informed of the critical events. Before participating in a 30minute training session to familiarize them with the driving simulator, participants adjusted the driver's seat to their own preferences. In the training session, participants first drove on a rural road for 20 min to become accustomed to the lack of physical motion feedback and practice staying in the lane and obeying speed limits. The track became increasingly complex over time (more curves, slopes, traffic, and environmental objects). On a separate track, participants practiced more dynamic driving maneuvers, including a slalom, emergency braking, and avoiding a sudden obstacle. After a short break, participants drove the first test track with only one critical event either with or without the secondary task; this drive took 15–20 min. Finally, participants drove the second test track consisting of all four scenarios presented three more times. The sequence of the repeated events was randomized in three blocks, where each block contained all four scenarios in random order. The second drive took 50–60 minutes.

2.8. Field test

The field study was conducted by the Institute of Automotive Engineering at the Technische Universität Braunschweig. The structure and timing of the critical events in the field study were designed to be comparable to the urban setting of the driving simulator study. However, due to safety concerns, none of the participants were distracted by a secondary task.

Fourteen people participated in the field study (three women). Participants' ages ranged from 23 to 26 years (M = 23.9 years, SD = 1.0 years). All participants had their driver's licenses for M = 6.5 years (SD = 1.6 years). About 36% of the participants drove up to 3,000 km per year while 28% drove between 3,000 and 9,000 km per year, and another 36% drove between 9,000 and 20,000 km per year.

To maintain controlled and reproducible conditions, the field study was conducted on a test track. A speed limit of 50 km/h was used. Pylons were used to mark the edge of the roadway. In contrast to the driving simulator studies, the test scenarios consisted of short sections (250 m) during which the critical events were triggered. For economic reasons, no fill scenarios were used. Similar to the simulated urban environment, the critical event was a previously hidden dummy crossing the roadway from the right side at a speed of 2 m/s. The distance from which the pedestrian was triggered was 28 m (scenario S), 31 m (scenario BS), or 33 m (scenario B), depending on the scenario. No car following scenario was utilized. Each participant drove each scenario once. To reduce the initial expectancy of an event, drivers were introduced to a cover story and instructed to drive straight toward a parked dummy vehicle to test the performance of an onboard sensor. In this arrangement, the trajectory and speed could be controlled and the drivers did not expect the critical event. In contrast to the driving simulator studies, expectancy could not be randomized across the scenarios. Due to technical limitations, the sequence of the scenarios was fixed at B followed by S and then BS.

2.9. Data analysis

Driver behavior was analyzed with regard to type of response (steering vs. braking) and speed of response. The driver responses were first classified as "braking only" (br), "steering only" (st), "combined response" (br + st), and "no response" (none). Based on these classifications, braking response times were calculated for cases in which the driver executed a braking response alone or followed by a steering response. Analogously, steering response times were calculated for cases that involved steering responses alone or followed by a braking response.

Overall, data from 1,703 events (131 participants) was recorded in the simulator studies, and data from 42 events (14 participants) was collected in the field test. The 102 cases (6.0%) in which driving speed fell outside of the defined limits (urban: 40–60 km/h; rural: 85–115 km/h; highway: 110–150 km/h) were excluded from the data analysis to preserve the comparability of the scenarios. After this procedure, the average initial speeds when the critical events were triggered were M = 48.9 km/h (urban; SD = 3.2 km/h), M = 99.9 km/h (rural road; SD = 5.6 km/h), and M = 129.4 km/h (highway; SD = 5.6 km/h). Three cases (0.2%) included braking response times of $\leq$ 300 ms; they were excluded from the analysis because they were too short to represent a plausible response to the actual critical event. It is more likely that these cases resulted from the driver merely regulating the speed. Due to recording errors, collision data for 107 cases (6.3%) was missing from the urban setting in the simulator. As a result of technical errors, the recordings of 12 cases (28.6%) in the field test could not be used for analysis.

Naturally, every driver may react differently in a given situation, which implies that there might not be a steering response time for every participant in every condition, for example. Despite the fact that each driver experienced every scenario multiple times, a repeated measurement analysis was not feasible due to dependency on the driver's response. For this reason, data analysis was conducted at the level of trials instead of subjects. As different trials of one subject are treated as independent, this approach might result in an underestimation of the population variance and, in turn, lead to a higher statistical power, however, at the cost of a higher false positive probability than the p-value suggests (resulting in more progressive inferences about the null hypothesis). This increased sensitivity should be kept in mind as readers make inferences about the population. As the authors were aware of this issue, they also relied on effect size measures and the graphical interpretation of the data (practical relevance of the mean differences) when making inferences.

The main results are presented in graphical displays of frequencies (maneuver choices and collision rates) and mean values (response times). For statistical inferences between groups, the corresponding confidence intervals of the means and multinomial proportions (Fitzpatrick and Scott, 1987) are provided. Further analyses were run to provide statistical inferences for the overall effects. The data on response choice was analyzed by means of Chi^2 tests of independence. Multifactorial analyses of variance (Type I SS) and *t* tests were used to analyze braking and steering response times. A binary logistic regression was used to analyze collision rates in the different scenarios. P-values of $p < .05$ are reported as significant.

Data processing, classification of responses and calculation of response times was done using Matlab 2014 (Mathworks). R (The R Foundation) and SPSS 23 (IBM) were used for statistical analysis.

3. Results

The following sections will cover the analyses of the driving data. To check validity, data from the simulated urban environment was compared to the field test data. The effects of distraction and expectancy were then analyzed using the initial (unexpected) and repeated (expected) events. Finally, the effects of environmental settings and scenario types were analyzed in relation to driver behavior and crash data using only the repeated events, since these events were most comparable in terms of distraction and expectancy.

3.1. Driving simulator versus field environment

A separate field test was conducted to put the findings of the simulator studies into perspective. To match the conditions of the field test as closely as possible, only the cases of subjects who drove scenario B in the first trial of the simulator study were used. Those first trials were compared to scenario B (first event) of the field test. Due to the short test track in the field test, expectancy was high in the second and third events (scenarios S and BS). To account for the high expectancy in scenarios S and BS, cases from the final trial (block 3) of the simulator study were used. Maneuver choices were analyzed for each of the specified cases. Regarding response times, one more differentiation was made. Since steering maneuvers were almost exclusively shown in the second and third trials of the field test, only these scenarios could be used to calculate the steering response times. For the remaining response times (accelerator release, pedal change, and braking), the unexpected trials of scenario B were used. To match the conditions of the field test, the same trials from the driving simulator study were used.

Regarding drivers' maneuver choices, no statistically significant differences were found between the two setups. This result indicates that drivers in the driving simulator chose responses similar to those selected in a more realistic field environment. The relative frequencies of the responses, sample sizes, and test statistics are displayed in Table 1. In both setups, the scenarios worked as intended. In scenario B, nearly all responses were braking maneuvers. In scenarios S and BS, braking maneuvers accounted for 40% of the cases, combined and steering maneuvers accounted for 30–50% and 10–20% of the cases.

In addition to the braking and steering response times, the accelerator release times and pedal change times (accelerator release to brake onset) were calculated to compare the two setups. As shown in Fig. 5, the onset of pedal responses was around 150 ms faster in the field test compared to the driving simulator. However, the difference was only statistically significant in case of the braking response times (accelerator pedal release: $t(19) = 1.78$, $p = .091$, $d = .78$; brake onset: $t(19) = 2.21$, $p = .039$, $d = .98$). Pedal change time and onset of the steering responses showed smaller effect sizes and did not differ significantly between the two setups (pedal change: $t(19) = .38$, $p = .711$, $d = .16$; steering onset: $t(15) = .85$, $p = .407$, $d = .42$).

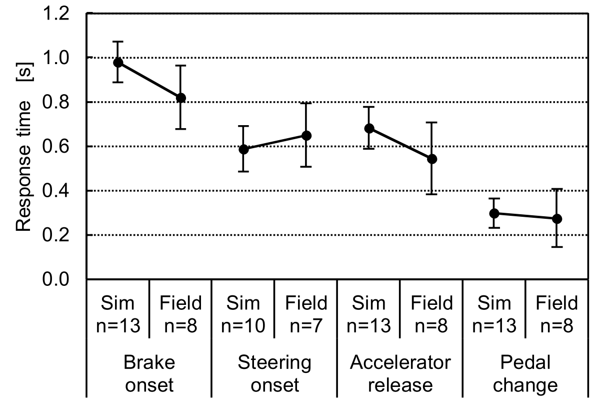

Fig. 5. Average response times in the simulated and field environment. Sample sizes (*n*) refer to the number of responses in each condition. Error bars represent 95% CIs of the mean response times. (Sim: driving simulator).

As it was not possible to completely match the simulated and field environments, some differences between the setups were expected (see also methods and discussion). Since the absolute differences were small, the results suggest that the initial responses and response times of both setups are comparable.

3.2. Secondary task

During the first trial of the three simulator studies, half of the participants were introduced to a secondary task (counting backward in steps of seven). In all three environmental settings, the secondary task had no statistically significant effect on maneuver choice, indicating no difference in the response patterns between distracted and undistracted drivers (urban: $X^2(3, N = 46) = 2.17$, $p = .538$, $V_{Cramér} = .22$; rural: $X^2(2, N = 40) = .40$, $p = .818$, $V_{Cramér} = .10$; highway: $X^2(2, N = 43) = .75$, $p = .687$, $V_{Cramér} = .13$).

Similarly, analyses of variance (environmental setting × secondary task) revealed that the secondary task had no statistically significant effect on braking ($F(1, 49) = 2.84$, $p = .098$, $\eta_p^2 = .06$) and steering response times ($F(1, 60) = .03$, $p = .857$, $\eta_p^2 < .01$). There were no statistically significant interactions between secondary task and environmental setting for braking ($F(2, 49) = 1.20$, $p = .309$, $\eta_p^2 = .05$) and steering response times ($F(2, 60) = .42$, $p = .661$, $\eta_p^2 = .01$).

Table 1
Relative frequencies, sample sizes, and test statistics of driver responses in the simulated and field environments separated by scenario type (B: braking possible; BS: braking and steering possible; S: steering possible).

		Driver response [%]					Chi^2-test of independence		
Scenario	Setup	Braking	Combined	Steering	None	*n*	X^2	*p*-value	*Cramér's V*
B	Sim	92.9	0.0	0.0	7.1	14	2.59	0.459	0.32
	Field	*75.0*	*8.3*	*8.3*	*8.3*	*12*			
BS	Sim	41.7	50.0	8.3	0.0	12	2.29	0.514	0.32
	Field	*45.5*	*27.3*	*18.2*	*9.1*	*11*			
S	Sim	42.9	35.7	14.3	7.1	14	0.56	0.905	0.16
	Field	*42.9*	*42.9*	*14.3*	*0.0*	*7*			

Table 2
Relative frequencies of driver responses in the first (unexpected) and repeated events (expected) separated by scenario type (B: braking possible; BS: braking and steering possible; S: steering possible) and environmental setting.

			Driver response [%]					Chi² test of independence		
Setting	Scenario	Trial	Braking	Combined	Steering	None	*n*	X^2	*p*-value	*Cramér's V*
Urban	B	First	93.3	0.0	0.0	6.7	15	2.70	.441	.13
		Repeated	*83.8*	*11.8*	*1.5*	*2.9*	*136*			
	BS	First	43.8	25.0	25.0	6.3	16	7.76	.051	.27
		Repeated	*47.7*	*44.3*	*6.8*	*1.1*	*88*			
	S	First	13.3	33.3	13.3	40.0	15	42.62	< .001	.47
		Repeated	*48.3*	*40.0*	*9.4*	*2.2*	*180*			
Rural	B	First	85.7	14.3	0.0	0.0	14	0.98	.322	.08
		Repeated	*73.6*	*26.4*	*0.0*	*0.0*	*125*			
	BS	First	15.4	76.9	7.7	0.0	13	9.92	.019	.27
		Repeated	*21.0*	*33.9*	*39.5*	*5.6*	*124*			
	S	First	30.8	15.4	53.8	0.0	13	5.16	.160	.19
		Repeated	*13.6*	*42.4*	*41.6*	*2.4*	*125*			
Highway	B	First	13.3	20.0	66.7	0.0	15	6.04	.109	.21
		Repeated	*30.5*	*34.4*	*34.4*	*0.8*	*128*			
	BS	First	0.0	0.0	100.0	0.0	14	4.66	.199	.18
		Repeated	*4.7*	*19.4*	*74.4*	*1.6*	*129*			
	S	First	0.0	35.7	64.3	0.0	14	1.47	.479	.10
		Repeated	*3.1*	*22.8*	*74.0*	*0.0*	*127*			

3.3. Expectancy

Each participant experienced one of the three basic scenarios (B, BS, S) without any expectancy before driving all scenarios three more times. This procedure was the same for all three environmental settings. To estimate the effect of expectancy, the first event was compared to the three repeated events. Since the secondary task produced only small effect sizes, distracted and undistracted drivers were aggregated to increase sample size for the first event. Furthermore, while the response times in the first repeated event were considerably shorter than those in the initial event, response times only decreased marginally in the second and third repeated events compared to the first repeated event. For this reason, the three repeated blocks were aggregated and treated as a single repeated condition.

Regarding maneuver choice, only some of the scenarios indicated that expectancy had a statistically significant effect (see Table 2). In the urban setting, there was a significant effect of expectancy for scenario S and a tendency for scenario BS. While 40% of the drivers did not react in the first trial of scenario S, this proportion dropped to 1–2% in the repeated trails. This result indicates that prepared drivers were better able to execute avoidance maneuvers. However, in the repeated trials of scenarios S and BS, drivers mainly used braking and combined maneuvers, but only 7–10% of the drivers used steering maneuvers that would have matched the requirements of the situation (see Fig. 6). The rural setting showed a five-fold increase of the use of steering maneuvers in scenario BS, indicating an adjustment to the situational requirements. However, in scenario S and the steering scenarios of the highway setting, no effect of expectancy was found, since the proportion of steering maneuvers was already high in the first trial (see Table 2). In the braking scenarios no significant effect of expectancy on driver responses was found. However, drivers in the highway setting showed some adjustment to scenario B (see Fig. 6). Use of steering maneuvers dropped from 67% to 34%. At the same time, braking maneuvers increased from 13% to 31%, indicating a better fit between driver response and situational requirements.

Regarding response times, analyses of variance (environmental setting × scenario type × expectancy) revealed an effect of expectancy on both braking response times ($F(1, 670) = 80.62$, $p < .001$, $\eta_p^2 = .11$) and steering response times ($F(1, 558) = 18.42$, $p < .001$, $\eta_p^2 = .03$). On average, braking response times in expected situations decreased by 330 ms (urban), 190 ms (rural), and 200 ms (highway). Steering response times decreased by 200 ms (urban), 90 ms (rural), and 160 ms (highway) on average (see Fig. 7). Additionally, environmental setting had an effect on both braking response times ($F(2, 670) = 93.03$, $p < .001$, $\eta_p^2 = .22$) and steering response times ($F(2, 558) = 69.69$, $p < .001$, $\eta_p^2 = .20$). Scenario type also had an effect on braking ($F(2, 670) = 4.43$, $p = .012$, $\eta_p^2 = .01$) and steering response times ($F(2, 558) = 23.90$, $p < .001$, $\eta_p^2 = .08$). The effects of

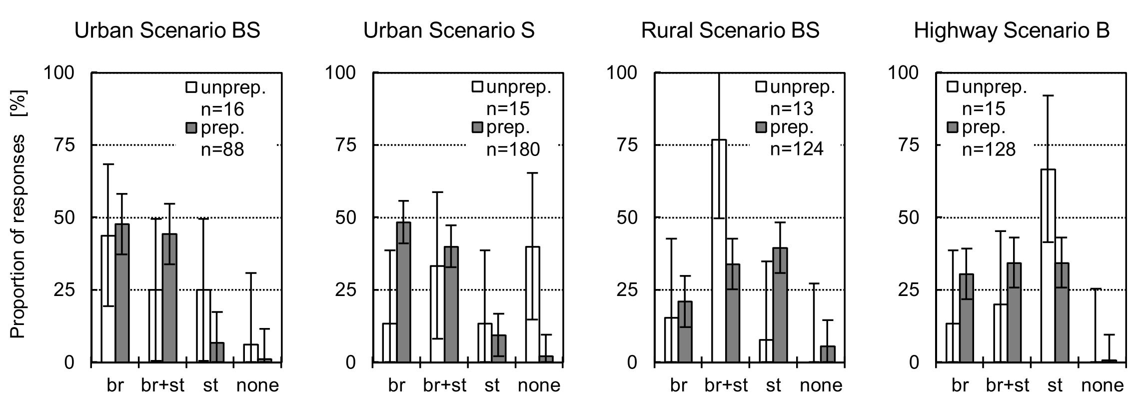

Fig. 6. Proportion of different responses in unprepared and prepared drivers in selected scenarios. Sample sizes (*n*) refer to the number of responses in each scenario. Error bars represent simultaneous 95% CIs of the multinomial proportions (Fitzpatrick and Scott, 1987). (B: braking possible; BS: braking and steering possible; S: steering possible; br: braking response; st: steering response; br + st: combined response; none: no response).

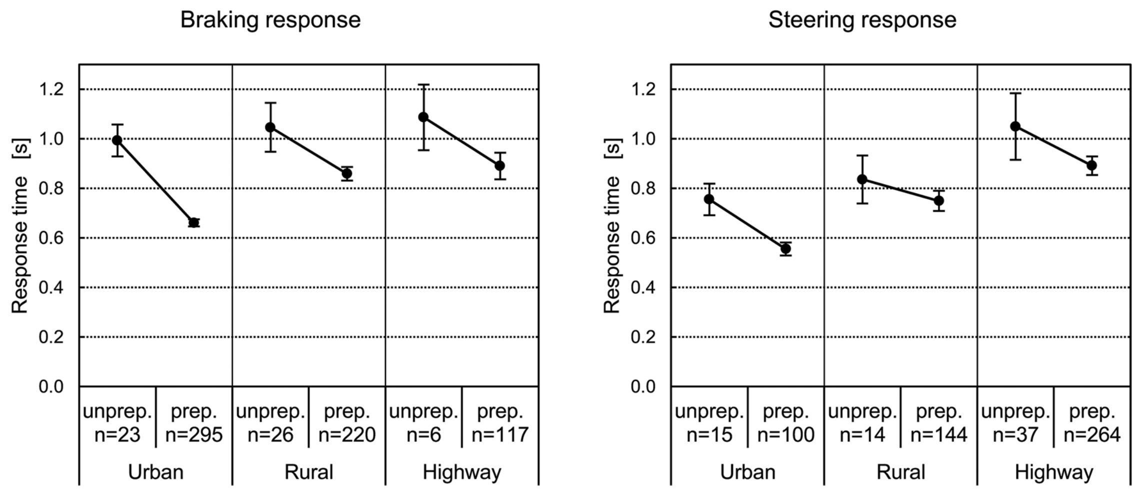

Fig. 7. Average braking response times (left) and steering response times (right) in unprepared and prepared drivers separated by environmental setting. Sample sizes (n) refer to the number of responses in each condition. Error bars represent 95% CIs of the mean response times.

environmental setting and scenario type are covered in detail in the following section, considering only the expected events since these cases were most comparable. Statistically significant interactions were found for the braking response times (environmental setting × scenario type: $F(4, 670) = 2.84$, $p = .024$, $\eta_p^2 = .02$; environmental setting × expectancy: $F(2, 670) = 3.80$, $p = .023$, $\eta_p^2 = .01$) and steering response times (environmental setting × scenario type: $F(4, 558) = 2.45$, $p = .045$, $\eta_p^2 = .02$). However, these results will not be interpreted further due to their inconclusive p-values (all $p \geq .023$) and small effect sizes (all $\eta_p^2 \leq .02$) (see discussion in Section 2.9 *Data analysis*). All other interactions reached no statistical significance (all $p \geq .068$).

3.4. Environmental setting and scenario type

To examine the influences of environmental setting and scenario type, the cases from the repeated events were used. These events were most comparable, since in all of these cases, drivers had no secondary task and were equally prepared because they had already encountered one critical event.

3.4.1. Maneuver choice

Fig. 8 presents the responses for each scenario type (LV, B, BS, and S) in the three environmental settings (urban, rural, and highway). Groups indicated by different letters had significantly different response distributions (Chi[2] test of independence: $p < .05$). All groups indicated by the same letter showed no statistically significant difference ($p > .05$).

For each environmental setting, the response patterns in the braking scenarios (LV and B) were very similar and differed significantly from the patterns in the steering scenarios (S and BS), which, again, were very similar to each other (see Fig. 8)

Maneuver choice depended on both scenario type and environmental setting. As expected, in all three environmental settings, steering responses (either alone or in combination with braking responses) occurred mainly in scenarios S and BS (1.5–6.2 times more frequently than in LV and B) while braking responses were more prominent in scenarios B and LV (1.9–8.3 times more frequently than in S and BS; see Fig. 8). However, these patterns differed between the three environmental settings. Fig. 8 illustrates that steering maneuvers occurred more frequently in settings with higher speed limits. In the urban setting, most driver responses were braking maneuvers. Even in scenarios S and BS, steering maneuvers occurred in only 7–10% of cases, and braking responses were shown in 48% of cases. In the rural setting, steering maneuvers were more frequent. In scenarios S and BS,

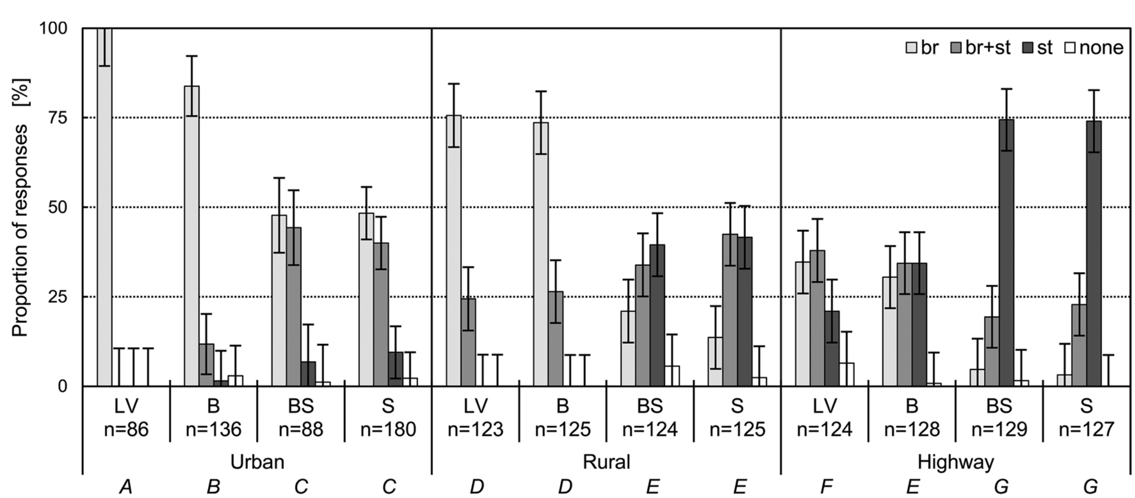

Fig. 8. Proportions of the different responses in the four scenarios (LV: leading vehicle; B: braking possible; BS: braking and steering possible; S: steering possible) and the three environmental settings. Sample sizes (n) refer to the number of responses in each scenario. Error bars represent simultaneous 95% CIs of the multinomial proportions (Fitzpatrick and Scott, 1987). Groups with different letters (A–G) were significantly different (Chi[2] test of independence: $p < .05$). (br: braking response; br + st: combined response; st: steering response; none: no response).

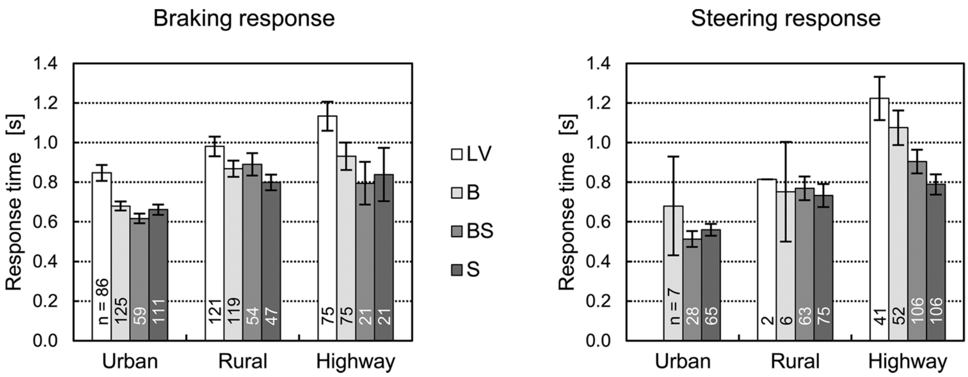

Fig. 9. Average braking response times (left) and steering response times (right) separated by scenario (LV: leading vehicle; B: braking possible; BS: braking and steering possible; S: steering possible) and environmental setting. Sample sizes (*n*) refer to the number of responses in each condition. Error bars represent 95% CIs of the mean response times.

the proportions increased to 42% and 40%, and braking maneuvers decreased accordingly (14% and 21%). This trend continued in the highway setting. In contrast to the urban setting, 79% of all driver responses in the highway setting were steering maneuvers (either alone or in combination with braking responses) that occurred mainly in scenarios S and BS. To some extent, even in the braking scenarios (LV and B), drivers chose steering maneuvers (21% and 34%) and combined maneuvers (38% and 34%). Furthermore, in scenario BS (braking and steering are possible), drivers' responses were essentially identical to those in scenario S. This result indicates that in a situation in which a driver had the opportunity to choose between braking and steering, a steering maneuver was chosen more frequently.

3.4.2. Response times

An analysis of variance (environmental setting × scenario type) was used to analyze the braking and steering response times. Regarding the braking response times, scenario type had an effect ($F(3, 902) = 42.28$, $p < .001$, $\eta_p^2 = .12$). This effect was mainly due to scenario LV. In this scenario, average braking response times were longer compared to the other scenarios (see Fig. 9 left; urban: 191 ms, rural: 129 ms, highway: 279 ms).

When the three environmental settings (urban, rural, and highway) were compared, braking responses were found to be slower in settings with higher speed limits ($F(2, 902) = 132.16$, $p < .001$, $\eta_p^2 = .23$, see Fig. 9 left). Braking responses were fastest in the urban setting; responses in the rural setting were 134–273 ms slower (see Fig. 9 left, post-hoc comparison: mean difference = 200 ms, $p < .001$). Responses in the highway setting were comparable to those in the rural setting, though scenario LV showed an increase of 153 ms. This increase led to a small interaction of the factors environmental setting and scenario type ($F(6, 902) = 3.29$, $p = .003$, $\eta_p^2 = .02$).

Regarding steering response times, scenario type had an effect ($F(3, 540) = 29.41$, $p < .001$, $\eta_p^2 = .14$). This effect was mainly due to the scenarios in the highway setting. In this setting responses were around 200–400 ms slower in scenarios LV and B compared to BS and S (see Fig. 9 right). As a result, a small interaction between the factors environmental setting and scenario type was found ($F(5, 540) = 2.50$, $p = .030$, $\eta_p^2 = .02$). As in the case of braking responses, environmental setting had an effect on steering response times ($F(2, 540) = 85.00$, $p < .001$, $\eta_p^2 = .24$). Steering response times were fastest in the urban setting and 172–256 ms slower in the rural setting (see Fig. 9, post-hoc comparison: mean difference = 203 ms, $p < .001$). The slowest steering response times occurred in the highway setting, and an increase of 57–135 ms was found in comparison with the rural setting (post-hoc comparison: mean difference = 97 ms, $p < .001$).

3.4.3. Collisions

Finally, the same cases discussed in the previous section were used to compare the collision rates depending on the drivers' responses in each of the four scenarios in the three environmental settings. Table 3 presents the collision rates aggregated for the three factors and the two-way interactions. Fig. 10 displays descriptive statistics for the proportion of driver responses split by cases that did and did not involve a collision. Additionally, the data labels represent the collision rates for a specific driver response P(collision | response). For example, considering scenario S in the urban setting, about 47% of the 138 responses were braking maneuvers (complete stacked bar). This 47% consist of 11% of the responses in which a driver braked and had no collision (white bar) and 36% in which a driver braked and had a collision (black bar). The data label displays the collision rate in all braking responses of scenario S (77%; equal to the proportion of the black bar in the complete stacked bar).

When the aggregated collision rates in Table 3 are compared, braking responses seem to be related to a higher collision rate. Furthermore, while the maneuver choices within the braking scenarios (LV and B) and within the steering scenarios (BS and S) were almost identical (see Fig. 8 in Section 3.4.1 *Maneuver Choice*), scenarios LV and S showed increased collision rates compared to scenario B and BS, respectively. Finally, the descriptive statistics illustrate that most crashes occurred in scenario LV in the highway setting and scenario S in the urban setting (see Table 3, interaction of setting and scenario type).

To gain insight into these relationships, two models were fitted to the data: (1) a logistic regression with environmental setting and scenario type as predictors and (2) a logistic regression with the addition of response time as a covariate. The summaries of both models are presented in Table 4, and the test statistics of model 2 are presented in Table 5. As the interpretation of the odds ratios of the interaction terms is not straightforward, the coefficients produced by the logistic regression model were used to calculate odds relative to the reference category (Highway setting, scenario S). In this way, the relative odds of an interaction can be compared to the reference category analogous to the relative odds of the main effects. The relative odds of both models are displayed in Fig. 11.

The relative odds of model 1 showed a pattern similar to the one found in the descriptive statistics (compare Table 3 interaction of setting and scenario type and Fig. 11 left) that resulted in an interaction of the factors environmental setting and scenario type. However, the odds of model 2 decreased in scenario LV in the highway setting. This result seems plausible when maneuver choice is considered (Fig. 10). In this specific situation, most of the responses were braking responses either alone (37%) or followed by steering responses (27%) that were associated with collision rates of .47 and .63, respectively. As this scenario was designed as manageable with an immediate braking response (just as scenario B), it can be inferred that the high collision rates in this scenario are related to too slow responses (compared to scenario B), as reported in Section 3.4.2 *Response times*. In addition, the relative odds of scenario S in the urban setting increased compared to those of model 1. This result again seems plausible when maneuver choice is considered (Fig. 10). Similarly, most of the responses in this situation were braking responses either alone (47%) or followed by a steering response (17%) that were associated with collision rates of .77 and .52, respectively. However, in scenario S, response time did not matter because collisions

Table 3
Aggregated descriptive statistics of the collision rates for the three factors and two-way interactions. (br: braking response; br > st: combined response, braking first; st > br: combined response, steering first; st: steering response; LV: leading vehicle; B: braking possible; BS: braking and steering possible; S: steering possible).

	Scenario type				
Driver response	LV	B	BS	S	*Total*
br	0.25	0.18	0.17	0.78	*0.29*
br > st	0.63	0.30	0.07	0.37	*0.35*
st > br	0.53	0.18	0.02	0.17	*0.17*
st	0.54	0.05	0.02	0.05	*0.07*
Total	*0.36*	*0.19*	*0.06*	*0.29*	

	Scenario type				
Environmental Setting	LV	B	BS	S	*Total*
Urban	0.09	0.10	0.12	0.51	*0.25*
Rural	0.35	0.27	0.07	0.27	*0.24*
Highway	0.53	0.18	0.02	0.07	*0.20*
Total	*0.36*	*0.19*	*0.06*	*0.29*	

	Environmental Setting			
Driver response	Urban	Rural	Highway	*Total*
br	0.27	0.29	0.35	*0.29*
br > st	0.32	0.33	0.38	*0.35*
st > br	0.16	0.16	0.20	*0.17*
st	0.00	0.08	0.07	*0.07*
Total	*0.25*	*0.24*	*0.20*	

could only be avoided with a steering response (opposed to scenario BS). Thus, since steering responses were used less frequently in the urban setting, inclusion of the covariate in model 2 emphasizes the effect of an incorrect maneuver choice.

To summarize, the higher collision rates found in braking responses can be related to too slow braking responses in scenario LV and wrong maneuver choices in scenario S. Inappropriate response times appeared more frequently in the highway setting while inappropriate maneuver choices appeared more frequently in the urban setting.

4. Discussion

A driving simulator was used to investigate the influence of scenario type (B: only braking possible, S: only steering possible, and BS: both possible) and environmental setting (urban, rural, and highway) on response time and maneuver choice in distracted and undistracted drivers in expected and unexpected situations.

The results showed that for scenarios in which a salient obstacle suddenly entered the vehicle's path (B, BS, and S), braking response times were very similar, with values around 650 ms in the urban setting and 800 − 930 ms in the rural and highway settings. These values are comparable to the expected situations reported by Green (2000). In a fourth scenario (LV), a leading vehicle reduced its velocity to a full stop, which constituted a less salient change in the environment. This more gradual event led to increased braking response times of 850 ms (urban), 980 ms (rural), and 1,130 ms (highway). Unlike in scenarios in which an obstacle suddenly appeared (as in B, BS, and S), drivers had to detect the change in velocity, which needs to exceed a certain threshold to be discriminated as safety relevant (Markkula et al., 2016). Accordingly, drivers need more time to respond to critical situations that evolve gradually due to longer detection and discrimination times. These slowly evolving situations offer a high potential for warning systems that highlight dangers drivers might not have noticed yet.

Furthermore, the onsets of braking and steering responses were found to be slower in settings with higher speed limits. To avoid a collision drivers had to execute a braking or steering maneuver. At higher travel speeds, the stopping distance for a braking maneuver and the travel distance during a steering maneuver become longer. This effect was taken into account when creating the scenarios to help ensure comparable criticality. As a result, the critical object in scenarios with higher speed limits was further away when it appeared on the road (or when it braked, in case of the leading vehicle scenario). In these cases, drivers responded more slowly; this behavior indicates that distance rather than available time headway determines the subjectively perceived criticality of a situation. Larger distances were associated with slower responses to the onset of the critical event. This result is similar to the effect of visual looming described by Markkula et al. (2016) in their evidence accumulation approach.

Furthermore, the delayed onset times seem to result in more deliberate responses. In the current study, steering responses can be seen as more elaborate, since the driver had to detect and judge the available space for bypassing the critical object instead of simply reducing the vehicle's velocity. Steering responses were more frequent in the highway setting while braking responses were more frequent in the urban setting. The rural setting lay somewhere in between. This result indicates that drivers more effectively adjust their responses to steering scenarios when they delay their responses. This effect may also be due to the fact that a swerving maneuver in the urban setting would have needed to be highly dynamic in order to avoid a collision. The longer headways in the rural and highway settings were not as demanding for drivers since this layout offered more (longitudinal) room for steering maneuvers.

The relevance of the differing response patterns becomes even clearer when the collision data is taken into account. In the steering scenarios in the rural and highway settings, steering maneuvers occurred in 43% (rural) to 75% (highway) of cases, indicating a good match between situational requirements and driver response. However, in the urban setting, 63% of responses were braking responses (either alone or followed by steering) and led to collisions in most cases. While steering responses resulted in less frequent crashes, they accounted for only 7% of cases. As a result, the most effective maneuver was employed least frequently, and the least effective maneuver was employed most frequently. This finding indicates that while drivers are capable of rapid responses, the mismatch between situational demands and

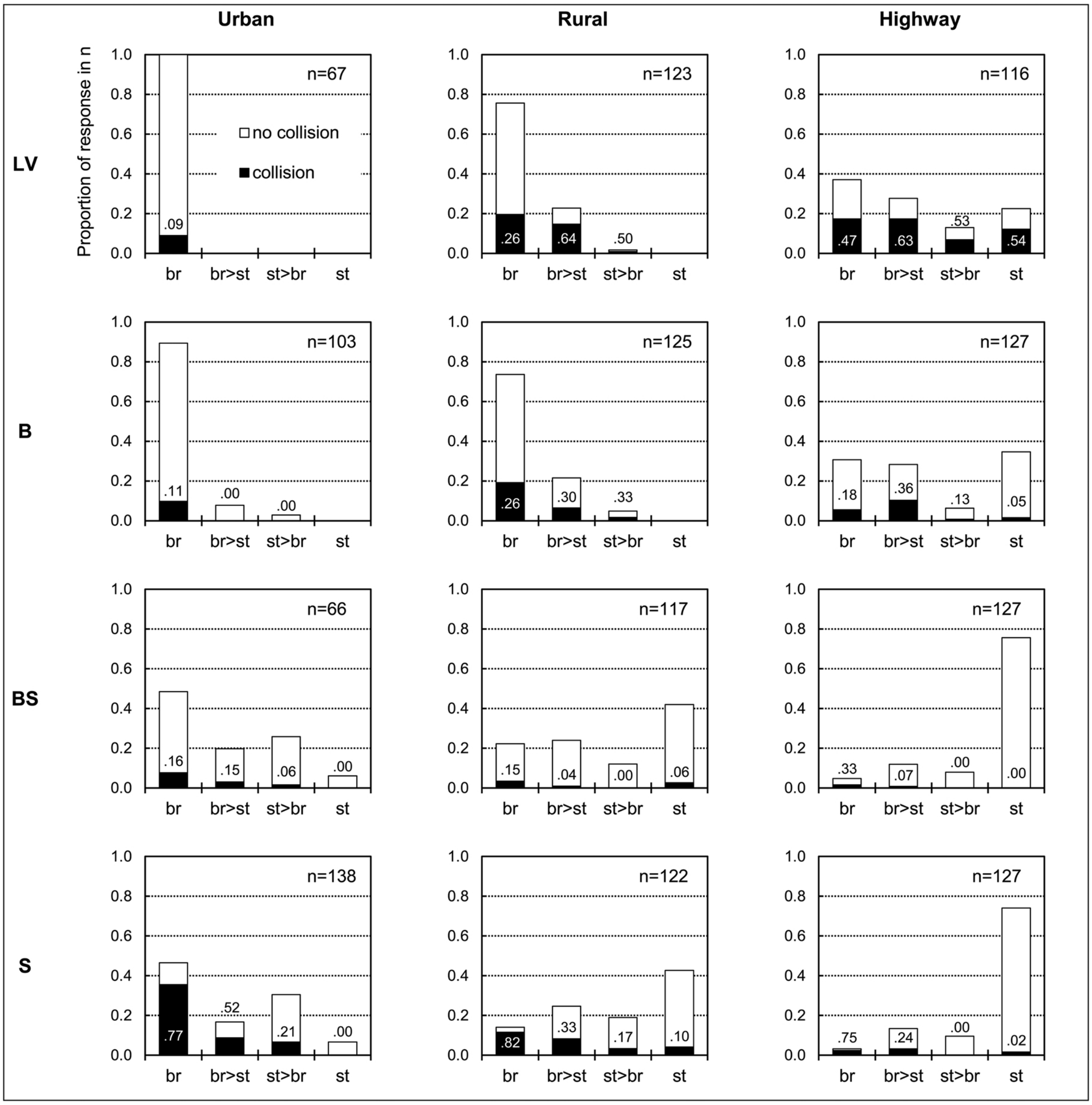

Fig. 10. Proportion of driver responses split by cases with and without collision separated for environmental setting and scenario type. Sample sizes (*n*) refer to the number of all responses in each scenario in each environmental setting. Data labels represent the proportion of collisions for a specific driver response P(collision | response) (see text for example). (br: braking response; br > st: combined response, braking first; st > br: combined response, steering first; st: steering response; LV: leading vehicle; B: braking possible; BS: braking and steering possible; S: steering possible).

Table 4
Summaries and comparison of model 1 and model 2.

	Nagelkerkes R^2	*−2 Log-Likelihood*	Omnibus test		
			X^2	df	*p*-value
Initial		1456.56			
Model 1	0.24	1226.20	230.36	11	< .001
Setting × Scenario					
Model 2	0.45	981.88	474.68	12	< .001
Setting × Scenario					
Covariate: Response time [ms]					

maneuver choices characterizes drivers' behavior in the urban setting as an automated response rather than a reasoned decision. These automated responses often result in braking maneuvers, a pattern that is in line with previous findings (e.g., Adams, 1994; Kaplan and Prato, 2012; Dozza, 2013). This finding emphasizes the idea that a driver assistance system must aim to not only improve response times but also support drivers in choosing adequate maneuvers for the given situation.

Furthermore, while a good match was found between driver behavior and situational demands at higher speed limits in the steering scenarios, more crashes were found in the braking scenarios compared to the lower speed limits. These crashes were a result of the slower braking responses found in the high speed settings, and it became more critical in the leading vehicle scenario in which the average collision rate was 53%. Here, braking response times were even longer. Since the delayed responses found at higher speed limits were linked to a change in maneuvers executed, it seems plausible to assume that the choice process also changed (see Donders, 1969). The findings suggest that, due to misjudgment of stopping distances at higher speed limits, drivers spend more time choosing a maneuver. In the steering scenarios, this relationship turned out as an advantage, since adequate steering maneuvers were used more frequently. However, in contrast to steering maneuvers, braking maneuvers are far less effective when executed too

Table 5
Test statistics for model 2: Binary logistic regression (crash vs. no crash) with the predictors environmental setting, scenario type, and response time in ms.

					95% CI of *Exp(B)*	
	Wald-X²	df	*p*-value	*Exp(B)*	LL	UL
Response time [ms]					1.004	1.006
Setting	90.61	2	< .001			
(ref. = Highway)						
Urban	76.86	1	< .001	72.685	27.881	189.490
Rural	25.10	1	< .001	11.563	4.438	30.128
Scenario type	42.51	3	< .001			
(ref. = S)						
LV	13.40	1	< .001	5.798	2.263	14.857
B	0.11	1	.744	1.183	0.430	3.257
BS	7.20	1	.007	0.097	0.018	0.533
Scenario type × Setting	90.61	6	< .001			
LV × Urban	65.77	1	< .001	0.003	0.001	0.014
LV × Rural	18.32	1	< .001	0.085	0.027	0.263
B × Urban	20.07	1	< .001	0.056	0.016	0.197
B × Rural	1.55	1	.213	0.472	0.145	1.540
BS × Urban	0.22	1	.642	1.568	0.235	10.454
BS × Rural	0.05	1	.828	0.808	0.118	5.545

late, which led to more collisions in the braking scenarios compared to the lower speed limits.

Regarding maneuver choice in general, the drivers adjusted their responses to the scenario type, as expected. Drivers tended to brake when no room was available for bypassing the obstacle; they swerved when the obstacle was too close and lateral room was available. When drivers had a choice of response (enough room to either bypass the vehicle or come to a full stop before a collision), they produced the same response pattern as in the steering scenario. This finding indicates that even though braking maneuvers seem to be to the most intuitive choice in a time-critical situation (like in the urban setting), steering maneuvers are preferred when a situation is not perceived as urgent (as in the rural and highway settings) in order to maintain constant travel speed (Summala, 2000). This finding also suggests that drivers do not to differentiate the distance to the collision object but only the presence/absence of lateral room for bypassing the object. The effect may be due to the fact that at higher speeds, headways and stopping distances are not as easily determined as room for bypassing. The width of an obstacle provides a rough estimate of the available space around it, even if this object is far away.

The current study found no statistically significant effect of cognitive distraction caused by a secondary task on either response time or maneuver choice. This result may be due to the smaller sample sizes in the initial event that only allowed larger effects to reach statistically significant levels. Additionally, since the drivers were not visually distracted, they were still able to detect relevant changes in the environment. All critical objects were easily recognizable and predictable once visible. For the situations used in this study, this result indicates that a cognitive task that does not include visual distraction does not degrade a driver's ability to detect and discriminate a sudden critical event. This result is in line with findings from naturalistic driving studies (Fitch et al., 2014; Victor et al., 2014) in which using a cell phone while driving (talking and listening without visual/manual distraction) had no effect or even improved driving performance. In these studies, drivers changed lanes less frequently and paid increased attention to the forward roadway when using a cell phone. However, it should be remembered that the findings from the current study might be specific to the chosen scenarios and events. In other setups in which discrimination between critical and non-critical objects is more ambiguous or the critical situation evolves more gradually, cognitive distraction may have a greater effect on overall response times.

Regarding expectancy of the situation, only in a few cases drivers showed a better adjustment of their response choices to the scenarios. This finding indicates that especially in the highly demanding urban setting, driving maneuvers still rely more on automated responses than refined decision processes. However, drivers responded significantly faster when an event was anticipated. Braking response times to unexpected events were 1.0 – 1.2 s, these results match those reported by other studies (Fitch et al., 2010; Summala, 2000). Compared to the unexpected events, braking responses were 200 – 350 ms faster (20 – 30%) in the repeated events, and steering responses were 90 – 200 ms faster (10 – 30%). On the one hand, these findings highlight the potential of warning systems aimed at increasing the driver's advanced preparedness for an event. On the other hand, the scenarios used in the current study were highly time-critical and evolved rapidly. An early warning may not be possible or even detrimental to driver performance (Naujoks et al., 2012).

Moreover, in line with previous research (e.g., Green, 2000), these findings stress the importance of expectancy. Since experimental designs frequently incorporate repeated trials to test multiple experimental conditions, within factors are often confounded with expectancy effects. This issue can be addressed by counterbalancing the order of the expressions of the within factor. However, expectancy effects will still increase the variance of response time measures. It may be worth to consider introducing one to three dummy events at the beginning of the test track to establish a certain amount of expectancy and only analyze the later events. If the absolute values of initial responses are of interest, other options include having each participant engage in only one event, introducing long pauses between events, and interrupting the sessions with non-driving tasks.

To put the findings of the simulator studies into perspective, a separate field test was run. Drivers in the driving simulator showed very similar responses compared to drivers in the more realistic field test environment. However, the response times for accelerator release and brake onset were 150 ms faster in the field test (20%). Several factors may have contributed to these differences. First, the field conditions could not be made completely identical to those in the driving simulator. The test track could only vaguely resemble a real urban roadway

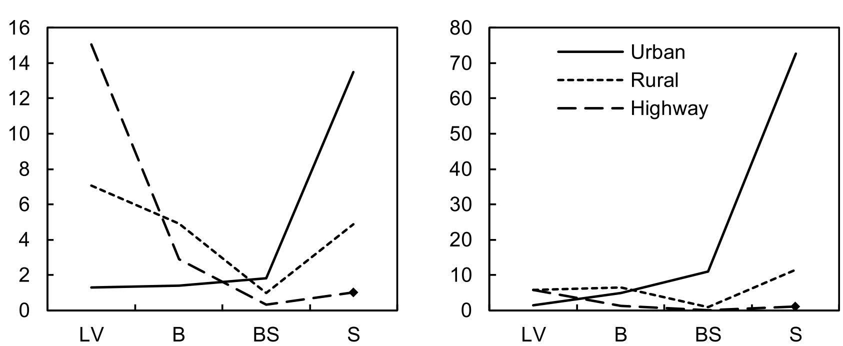

Fig. 11. Relative odds (crash/no crash) per condition calculated using the coefficients of a binary logistic regression without (left) and with response time as a covariate. Markers indicate reference category: Highway, Scenario S.

Table 6
Overview of the relevant findings and suggested test scenarios (B: braking possible; LV: leading vehicle; S: steering possible).

		Urban 50 km/h			Rural 100 km/h			Highway 130 km/h		
		B	LV	S	B	LV	S	B	LV	S
Braking response time [s]	Unexpected	0.98	–	0.96	0.97	–	1.21	1.10	–	1.04
	Expected	*0.68*	*0.85*	*0.66*	*0.87*	*0.98*	*0.80*	*0.93*	*1.13*	*0.84*
Steering response time [s]	Unexpected	–	–	0.73	–	–	0.87	1.33	–	0.96
	Expected	*0.68*	–	*0.54*	*0.75*	*0.82*	*0.73*	*1.08*	*1.22*	*0.79*
Braking %	**Unexpected**	93.3	–	13.3	85.7	–	30.8	13.3	–	0.0
Steering %		0.0	–	13.3	0.0	–	53.8	66.7	–	64.3
Combined response %		0.0	–	33.3	14.3	–	15.4	20.0	–	35.7
No response %		6.7	–	40.0	0.0	–	0.0	0.0	–	0.0
Braking %	***Expected***	*83.8*	*100.0*	*54.3*	*73.6*	*75.6*	*13.6*	*30.4*	*34.7*	*3.2*
Steering %		*1.5*	*0.0*	*7.2*	*0.0*	*0.0*	*41.6*	*34.4*	*21.0*	*74.0*
Combined response %		*11.8*	*0.0*	*37.0*	*26.4*	*24.4*	*42.4*	*34.4*	*37.9*	*22.8*
No response %		*2.9*	*0.0*	*1.5*	*0.0*	*0.0*	*2.4*	*0.8*	*6.4*	*0.0*

while the simulated environment was far more visually complex. This complexity might have increased the time needed to detect the critical object in the simulated environment. Furthermore, only a short test track without any fill scenarios could be used in the field test, and this arrangement may have increased drivers' alertness and expectancy of any kind of event. Finally, since the field study incorporated a real vehicle and obstacle on a roadway, the critical event may have constituted a more realistic danger and evoked stronger responses. Considering these constraints, a difference of 150 ms between the setups indicates a strong external validity of the driving simulator in terms of its ability to evaluate drivers' initial responses.

Some limitations apply to the findings of the current study. The experiments presented focused mainly on situational factors. As pointed out in the introduction, drivers may react differently depending on the actual task he or she is executing, even if all situational factors are held constant. A secondary task was introduced to estimate potential variations in the drivers' responses caused by cognitive distraction. While there was no effect observed for cognitive load, this might be due to the fact, that the main driving task was the same, namely "follow the lane at a constant given speed." However, in real traffic, a driver's main task may be different depending on the context. For example, time pressure may cause a driver to optimize his or her travel speed within the traffic flow, possibly at the cost of safety, as the driver may be more focused on traffic lights than monitoring the roadway. This kind of variations may be also caused by short-term tasks that were not included in the current study but are prominent in real traffic. Such tasks include searching for a parking lot, navigating in an unknown city or preparing to turn at an intersection. In all of these situations, a driver's focus of attention is likely to be shifted solely because he or she engages in a different task that might not even be visible. Different tasks were not included in this study and should be considered in future research.

Furthermore, the scenarios in the current study were designed to require an immediate response in order to ensure the comparability of the urgency. However, slowly evolving critical situations in particular represent high potential for driver assistance systems. To cover a broader range of use-cases for evaluating such systems, future research should include scenarios in which a driver typically fails to detect or discriminate a potentially dangerous event.

Finally, since the current study focused on situational factors, the samples used were chosen a priori to be homogenous in order to reduce the influence of personal factors. Since younger and older drivers are known to have a higher risk of involvement in a crash (Nef et al., 2015; Ouimet et al., 2015), future studies should feature heterogeneous samples to estimate the variation introduced by interpersonal differences. The same argument applies to driving experience. Since the level of driving experience was highly homogeneous in our sample, this factor should be considered in future research. Response times and maneuver choices are likely to be influenced by differences in hazard perceptions resulting from different levels of driving experience (Crundall et al., 2012; Muttart and Fisher, 2016).

5. Conclusions

This study systematically investigated the influences of global and situational characteristics of the driving environment on driver behavior in time-critical situations. The findings could help to establish a set of standardized test scenarios and lead to more comparable studies. Standardized scenarios could enhance future researchers' ability to make informed decisions about experimental design and in the long run support the accumulation of knowledge

Table 6 presents the relevant findings related to the response time and maneuver choice in expected and unexpected events. Response times are in the range of values found in previous studies that used critical situations (e.g., Fitch et al., 2010; Green, 2000; Summala, 2000; Sohn and Stepleman, 1998; Young and Stanton, 2007). However, the literature also reveals considerable variations in response times that presumably result from different expressions of global and situational factors that were systematically varied or controlled in the current study. The environmental setting (urban road, rural road, or highway) seems to be an essential factor for both, the driver's response time and maneuver choice. Within one setting, the chosen scenarios had a considerable influence on maneuver choice. However, with the exception of the car following scenario, the response time was not influenced by scenario type.

Depending on the objective of a study, different recommendations can be made on the basis of the current findings. If an area of application is not a priori limited to a specific speed limit, all three driving settings (urban, rural, and highway) should be incorporated to facilitate global interpretation of the findings. Use of different driving settings to cover speed limits of 50 (urban), 100 (rural), and 130 km/h (highway) is recommended, since the results for response times and maneuver choice can be expected to vary considerably.

If response time is of interest, the urgency of a situation should be great enough to require an immediate response from the driver. Regarding the scenarios, it is recommended that future studies use a setup in which an obstacle appears close to the vehicle but enough room for bypassing the obstacle is provided so that a steering maneuver is appropriate. These situations should be compared to situations in which the obstacle is located further away to make use of a braking maneuver possible. This differentiation can be expected to influence drivers' maneuver choice. Finally, saliency of the critical event influences response time. If drivers' response speed is of interest, rapidly evolving situations (e.g. an obstacle suddenly entering the road) should be compared to slowly evolving situations (e.g. a leading vehicle reducing speed). The combination of these recommendations results in a set of nine situations (see Table 6) that facilitate the analysis of response times and maneuver choice in relation to relevant global and situational factors.

Expectancy is likely to cause methodological issues in within-subject designs; it can influence both the drivers' response time and maneuver choice. In addition to counterbalancing the order of experimental conditions, the use of one to three dummy events is recommended to establish comparable expectations between the participants in the following events. Alternatively, if initial driver responses are of interest, a single event should be used for each participant or long pauses should be taken between critical events. This method would best resemble a critical situation in a real traffic environment.

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