Integrative Warning Concept for Multiple Driver Assistance Systems

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For my son Jonas

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Zusammenfassung

Die voranschreitende Entwicklung auf dem Weg zum automatisierten Fahren sowie Euro NCAP Vorgaben führen dazu, dass in den nächsten Jahren immer mehr warnende Fahrerassistenzsysteme (FAS) in europäische Fahrzeuge integriert werden. Zusätzlich können zukünftige FAS durch Car-2-X Kommunikation auf einen erweiterten sensorischen Horizont zurückgreifen und Fahrer früher und umfangreicher warnen. Es stellt sich die zentrale Frage im Rahmen dieser Entwicklungen, wie verschiedene Fahrerassistenzwarnungen in die Mensch-Maschine-Schnittstelle zukünftiger Fahrzeuge integriert werden können, und welche Warninformationen nötig sind, um die Akzeptanz, die Nützlichkeit und die Verständlichkeit aus Fahrersicht zu gewährleisten.

Ziel dieser Arbeit war es, ein Konzept zur Integration zukünftiger FAS zu entwickeln, welches frühe Kollisionswarnungen von ca. zwei Sekunden vor der letztmöglichen Warnung berücksichtigt. Dazu wurden zwei Fahrsimulatorstudien durchgeführt und spezifische Warnelemente untersucht. Zentrale Forschungsfragen waren: ob und wie Fahrer von Fahrerassistenzwarnungen profitieren, die Richtungs- und/oder Objekthinweise enthalten und wie diese sich auf die Akzeptanz eines integrativen Warnkonzeptes auswirken. Es wurde weiterhin untersucht, inwieweit generalisierte Warnungen für eine Gruppe verschiedener kollisionswarnender FAS genutzt werden können. Hierzu wurden kritische, frontale und laterale Fahrszenarien in ländlicher und städtischer Umgebung evaluiert. Außerdem wurden unnötige Warnungen und Fehlwarnungen untersucht.

Die Ergebnisse zeigen, dass insbesondere frühe FAS-Kollisionswarnungen, die Richtungsinformationen enthalten, den Fahrer im Rahmen eines integrativen FAS-Warnkonzeptes effektiv unterstützen und zu positiver Akzeptanz führen. Warnhinweise über die Art eines kritischen Objekts zeigen hingegen geringere Relevanz für die Fahrerperformanz und -akzeptanz. Abschließend werden im Rahmen dieser Arbeit Empfehlungen zur Warnintegration bezüglich zukünftiger FAS gegeben.

Abstract

More warning Advanced Driver Assistance Systems (ADAS) will be integrated into the European vehicles in the coming years, due to the ongoing progress on the way to automated driving and Euro NCAP requirements. Furthermore, upcoming technologies like Car-2-X will extend the sensory horizon of ADAS and enable the possibility to warn drivers earlier against various hazards than today. Regarding this progress, increasing numbers of different ADAS warnings will be communicated to the driver. In this context, an important question is how multiple ADAS warnings can be integrated into the Human Machine Interface (HMI) of vehicles and which warning elements are needed to ensure warning acceptance, efficiency and understandability seen from the driver's point of view.

Two driving simulator studies were conducted and the effects of specific warning elements examined to develop a concept for the integration of upcoming warning ADAS, which focuses on early collision warnings. The implemented early warnings were defined with a warning onset of approximately two seconds before the last possible warning onset. Main questions were whether and how drivers profit from warning direction cues and/or warning object cues for their response to a hazard, and how these cues affect the acceptance of an integrated warning ADAS approach. Furthermore, it was analyzed whether a generalized warning can be used for a cluster of different ADAS concerning the group "warning of collisions". Therefore critical scenarios in rural and urban surroundings were evaluated, including frontal and lateral (intersections) scenarios. Unnecessary warnings and false alarms have also been taken into account.

The results indicate that early warning direction cues have a high potential to assist drivers with an ADAS warning cluster which covers warning of collisions. In contrast, warning object cues seem to be less important for the drivers' performance and acceptance regarding early collision warnings. According to these findings, this thesis provides recommendations which warning elements should be included into future ADAS warnings in favor of an integrated warning approach.

Introduction

Chapter 1 of this thesis describes the motivation to examine an integrated driver centered warning approach for upcoming Advanced Driver Assistance Systems (ADAS). **Chapter 2** introduces the necessary theoretical background, starting with a description of the ADAS warning process, the driver model and the basics of collision avoidance. Besides, Chapter 2 includes a short description of human perception and attention because of their relevance regarding the effects of warnings. Subsequently it contains an overview of ADAS, the Human Machine Interface (HMI) and warning specificity. At the end of Chapter 2, the research questions are shown and methodical considerations discussed. **Chapters 3 and 4** present the two conducted main studies of this thesis, each with a description of the background, method, results and a discussion. At last, **Chapter 5** discusses the findings of this thesis, states recommendations for warning integration and closes with a final conclusion.

Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ANOVA	Analysis of Variance
BRT	Brake reaction time
C2X	Car-2-X (Car-2-Car and Car-2-Infrastructure Communication)
DAS	Driver Assistance Systems
Euro NCAP	European New Car Assessment Programme
FA	False alarms
FCA	Frontal Collision Alert
FOV	Field of view
FSRACC	Full Speed Range Adaptive Cruise Control
HMI	Human Machine Interface
LDW	Lane Departure Warning
LKA	Lane Keep Assist
OTW	Oncoming Traffic Warning
PW	Pedestrian Warning
RM-ANOVA	Repeated Measures Analysis of Variance
SDT	Signal Detection Theory
TTA	Time to arrival
TTC	Time to collision
UW	Unnecessary warning

Contents

1 Motivation

Due to the technical progress made, a growing number of multimedia, comfort and safety systems are developed to assist people living in our engineered society. On the one side, these systems help us to perform tasks more efficiently and with a higher level of comfort, on the other side, each newly developed system can also increase the learning effort to understand its usage. Thus, the design of the Human Machine Interface (HMI) plays a key role in achieving system understanding, good system acceptance and intended safety and comfort. Another important question is whether all of these new systems shall constantly provide us with different types of information and, if so, how this information can be handled by the users.

In the field of the automotive industry, road safety has always played a major role, in particular due to an increasing number of cars and thus traffic complexity. In 2012 approximately 27,800 people were killed by road traffic accidents in the EU (Statistisches Bundesamt, 2013). About 31% of accidents with personal injury took place in complex driving scenarios, e.g. with turning, changing direction, reversing, leaving traffic and right-of-way scenarios (Statistisches Bundesamt, 2013). In this context, a lack of driver attention has been identified as one of the leading causes of car accidents with an estimated percentage of 26% to 56% (Ho, Reed, & Spence, 2006). Nearly 90% of severe accidents could be positively influenced through an automatic or collision mitigating advanced driver assistance system (Winner, Hakuli, & Wolf, 2009). Consequently, in the past few years the automotive industry developed various ADAS to promote safe driving and reduce accidents as well as accident severity, e.g. ADAS like Forward Collision Warning (FCW or FCA) or Lane Departure Warning (LDW). In the upcoming years, vehicles will therefore be equipped with an increasing number of ADAS and many additional active safety functions are under development. For example the Delphi Study (2006) identified up to 91 assistance functions of which the 40 most useful where chosen through expert rating for further review (Lindberg, Tönert, Rötting, & Bengler, 2006). In addition to that, the Euro NCAP[1] will increase their requirements for vehicles equipped with ADAS for the next years, e.g. for Pedestrian Protection with pedestrian detection or Lane Keep Assist (Euro NCAP, 2012). Thus, in future, best Euro NCAP ratings can only be achieved by new vehicles that use well integrated ADAS.

Anticipating the next two decades, the automotive industry wants to achieve two main goals for ADAS: increased automation and thereby a higher level of comfort, and increased driver safety. To reach these goals, many safety and comfort relevant ADAS need to interact with the driver in a well-balanced way.

Safety relevant ADAS warn or inform the driver of emerging hazards using an integrated HMI. These ADAS warnings use different modalities, e.g. visual, auditory, or haptic modality, to alert the driver and assist him to respond fast and properly in critical driving situations. For example a Forward Collision Warning system warns the driver of an imminent collision using tone, vibration on the seat and a flashing symbol. Thereby it assists the driver to perceive the hazard and initiate collision avoidance responses. With increasing numbers of ADAS the number of different warnings may increase. The interaction of different warnings and their sheer number induces new scenarios that highlight the need of a integrative warning concept (e.g., Campbell, Richard, Brown, & McCallum, 2007; Lindberg, Tönert, Rötting, Systeme, & Bengler, 2006; Thoma, 2010). It is important that integrative warning concepts are characterized not only by scenarios in which warnings are presented in close proximity, but also by many different warnings using different comprehensible formats. The main question is how the amount of warnings and the subjectively experienced complexity of the whole warning process can be reduced and thereby comprehensibility and acceptance improved (e.g., Thoma, 2010).

[1]Euro NCAP is a vehicle safety rating system which is backed by the European Commission, seven European governments, as well as motoring and consumer organizations in every EU country.

As illustration a simplified example:

A vehicle (ego-vehicle) equipped with various ADAS approaches an X-intersection with the possibilities to drive straight, turn left and turn right. A group of running pedestrians also approaches this intersection and triggers a Pedestrian Warning (PW) of the ego-vehicle. After stopping and waiting for the pedestrians to move away, the ego-vehicle enters the intersection and starts to turn left. A fast oncoming vehicle approaches the ego-vehicle and triggers an alarm by an Oncoming Traffic Warning system (OTW). Now imagine the ego-vehicle is also equipped with a Frontal Collision Alert system (FCA), a Full Speed Range Adaptive Cruise Control (FSRACC), a Lane Keep Assist (LKA), a Lane Departure Warning (LDW), and with ADAS which broadcast advisory warnings, like emergency vehicle warnings and weather warnings. If every ADAS has to emit its own specific warning, the high number of different warnings and their differing comprehensible formats may lead to confusion for the driver. Ask yourself the question: Would you like to buy a car that emits many different warnings?

Questions regarding the integration of different warnings into one HMI have also been examined in the context of aviation. A main difference between aviation and road traffic is that drivers just want to drive their cars without going through a training regarding their cars' HMI, while pilots get an intensive training for their planes' HMI. Thus, this thesis focuses on an integrative warning approach for vehicles with the question which warning elements have to be communicated to the driver to ensure ADAS warning acceptance, efficiency and understandability. Furthermore, upcoming technologies like C2X will provide the possibility to warn drivers against hazards earlier than today. Hence, this thesis will examine early warnings which assist drivers to avoid collisions.

2 Theoretical Background

2.1 Process of Warning

In the following section I will provide a definition of “warning” and discuss dynamic warnings in the context of driving with the help of a warning process model. Furthermore, I will show a short overview of false alarms and unnecessary warnings because of their relevance to warning efficiency and warning acceptance.

2.1.1 Definition of Warning

A warning can be understood as rated information (ISO, 2005). Thus, a system or human has to process and weight perceived information to pass it as a warning to a recipient. A very important question is which elements a warning message should include. According to the ISO 16532 (2005), a warning should include the following elements:

- an element which attracts attention
- a reason for the warning (cause)
- a consequence if the warning is not observed
- instructions for actions.

Imagine that you are driving and your co-driver shouts in a loud voice: “Attention, a pedestrian!” In this case his loud voice will attract your attention, he will provide you information about the reason and maybe implicitly highlight the consequence. The warning of the mentioned example does not include the element of instructions for actions, but there is a high chance that you will respond right by hitting the brake. This example illustrates that not all recommended warning elements are needed for each warning scenario. The required warning elements seem to depend on the specific characteristic of the situation. The discussion which warning elements have to be communicated to the driver will be a main point of this thesis.

Edworthy & Adams (1996) separate a warning into two main aspects: an iconic aspect and an informational aspect. Iconic aspects are the requirements for warnings to get perceived and attended to by the receiver, e.g. for an auditory warning the audibility or loudness. In contrary, informative aspects inform the warning receiver about the quality of hazards and highlight possible responses. The iconic warning aspects correspond to the warning element which attracts attention in accordance with the ISO definition. The informative warning aspects can correspond to other elements of the ISO definition, but even more than that, e.g. the information about the location of a hazardous object. In section 2.1.2, I will discuss which warning elements can be helpful for warning drivers in the dynamic context of driving and how they interact.

In the context of driving vehicles, which are equipped with ADAS, warnings are used in a highly dynamic context and are strongly dependent on the timing. Usually ADAS warnings assist the driver to respond to emerging hazards, for example a suddenly braking leading vehicle. In most cases, the driver has limited time to respond to this hazard, therefore the right warning timing is essential. An early warning can lead to misinterpretation because relevant elements of the environment are not yet available for perception and evaluation. Drivers, who receive the warning “car coming from right” but do not see this car, may think the warning system does not work correctly. On the other hand, too late warning may distract the driver who started to perform a response to a hazard. Because future ADAS technologies (see section 2.4.3) will allow to alert drivers earlier, and little is known about driver behavior to early warnings, I will especially focus on early warning onset in the context of the effectiveness of specific warning elements.

2.1.2 Process Model of ADAS Warning

To illustrate how warnings interact in dynamic contexts like driving, a warning process model which illustrates different processing steps is helpful. I will introduce an integrative warning process model which takes into account the warning sender (ADAS), the warning design and the warning receiver (driver). It is based on the well-known Communication-Human Information Processing (C-HIP) model of Wogalter, Dejoy, & Laughery (1999). The C-HIP model describes multiple processing steps of a message receiver (human), like attending, comprehending and behaving to a message. Furthermore, the C-HIP model includes factors like attitudes, belief and motivation, which can influence the resulting behavior of the message receiver. Because these factors usually cannot be changed directly by warning systems and Wogalter's model does not specify processing steps on the message sender side nor the design of warning messages, I developed the integrative warning process model which is more suitable for the ADAS warning context, see Figure 2.1. As main elements I included the message sender, the message (warning) and the message receiver (driver), which are the key elements of the communication (e.g., Shannon & Weaver, 1976). The processing steps on the sender's side were adapted to Schmidt (2012) who also illustrated the warning sender as a system (ADAS). Basic properties of a warning message were included as high level overview. Furthermore, the processing steps of the receiver are mainly based on C-HIP model and extended by the element of encoding (Rogers, 2000) and anticipation (Schmidt, 2012). The resulting integrative warning model provides a systematic overview of key elements of the warning process in the context of ADAS warnings, see Figure 2.1.

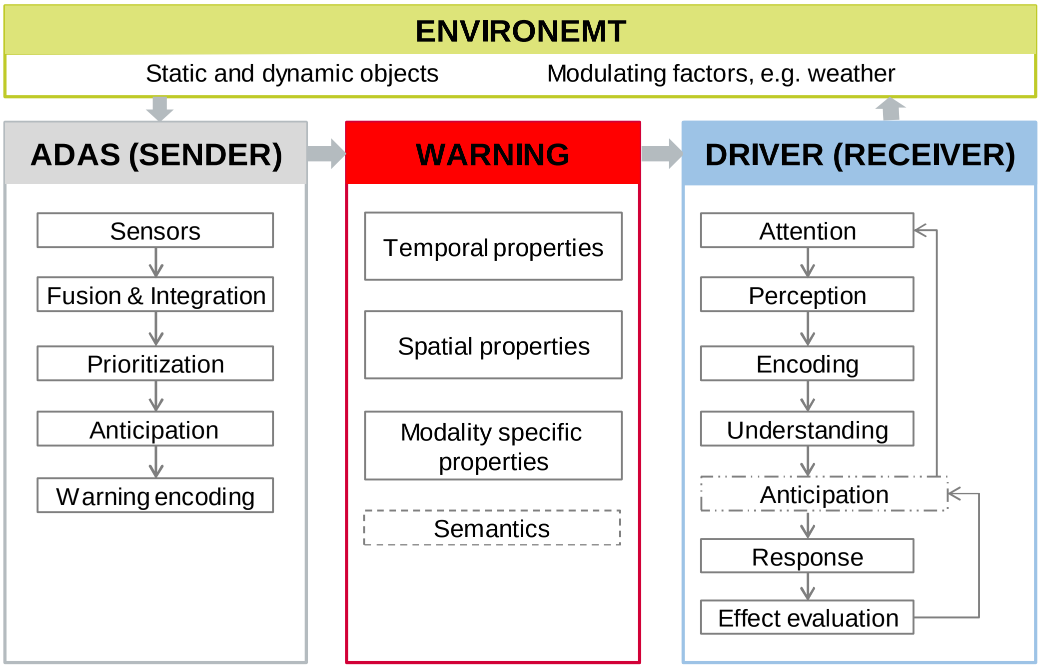


Figure 2.1: Integrative warning process model based on elements of the communication model of Shannon & Weaver (1976), the C-HIP model of Wogalter (2006), elements of encoding (Rogers, 2000) and anticipation in the context of the warning process (Schmidt, 2012). An ADAS integrates information of the environment and sends a warning with specific properties to the driver. The driver processes this warning and responds with an adequate action. Furthermore, the sender and driver are constantly connected in a feedback loop with the environment.

The integrative warning process model which is illustrated in Figure 2.1, defines the sender as ADAS, the message as warning and the receiver as driver. In the following I will describe the sequential processing steps, starting with the ADAS (sender). The ADAS uses multiple sensors and collects data of the environment. Through fusion and integration of sensory data, an algorithm can “anticipate” the risk of different identified objects with a specific likelihood-ratio. Relevant hazard candidates (objects) get quantified and prioritized by predefined criteria. A warning is encoded for objects with high priority. This step is important, because it determines which environmental information will be coded into the warning message. In most cases only few dynamic parameters are used to map information into a warning, e.g. criticality through auditory urgency mapping (see section 2.3.1). All other warning parameters are usually pre-defined (static) by the HMI algorithm. For the sender (ADAS), a high quality of detection and an optimal warning design are important to alert drivers reliably and appropriately.

Regardless of its modality, every dynamic warning has spatial properties (e.g., location, direction) and temporal properties (e.g., onset, duration). In combination with specific elements of different modalities, these properties represent warning semantics, which can be communicated to a driver (receiver). As described in section 2.1.1, a warning can contain different elements, to appropriately alert the driver, e.g. the cause of the warning.

After a warning message has been sent to the driver, he has to process the warning information, see Figure 2.1. The following processing steps on the driver's side are adapted to the C-HIP model of Wogalter (2006) and warning process model of Rogers (2000). For the driver the first step is to attend to the warning message. Facilitated by attentional resources, the driver notices the warning and encodes its semantics into his own semantic space. By association of warning semantics with information from the long-term memory and the environment, it can be comprehended. The processing of more informative warning aspects, e.g. the warning reason (cause), usually needs more cognitive resources than the processing of iconic aspects e.g. the loudness of a warning. Through repeatedly experiencing iconic aspects in a specific context, e.g. very loud alarm of an emergency vehicle, iconic aspects can become informative. Furthermore, the understanding of warning semantics depends on their perception, encoding and can be influenced through endogenous factors of the driver, e.g. motivation, states like fatigue, attitudes (Wogalter, 2006) and the exogenous context, e.g. weather and road surface.

After understanding the warning message, the driver should be able to anticipate (see section 2.2.2) the effects of the emerging hazard and his own action responses. Driver's anticipations are more accurate especially for situations that supplement the warning elements. Due to anticipation, drivers can respond to the warning and select an adequate action response to the hazardous situation. A warning can also lead to an action response of the driver without triggering an anticipation, especially for learned, habituated responses.

Four driver responses to a warning can be explained by the integrative process model: a shift of attention, an automatic behavioral response, a controlled behavioral response and the combination of these responses. Which kind of response is performed depends on the warning design and learned response patterns of the driver. For example the comprehended warning message can redirect (orient) the driver's attention to environmental aspects, which work as context cue and activate learned responses of the driver (automatic response). An example for a respective real traffic situation could be the following: A warning tone which redirects the driver's attention to the braking light of a leading car, which furthermore triggers a learned, automatic braking response of the driver (e.g., braking). On the contrary, a controlled driver response to a warning could be an overtaking maneuver to a stationary vehicle. In this case a prior warning led to an anticipation of the driver and the driver selected the necessary action responses to initiate the overtaking maneuver.

After a driver action response is performed, the driver evaluates its outcome and updates his action-effect associations in his memory, e.g. likelihoods for effects of specific action responses. Furthermore, the driver is acting in a feedback loop with the environment, thus his behavior leads to changes of the environment and new input for the sender (ADAS) and himself.

In addition to illustrated processing steps of Figure 2.1, Wogalter (2006) accents the interaction between all steps of message processing on the receiver's side. According to the C-HIP model, a not comprehended (warning) message will lead to an allocation of attention and re-encoding which means a jump to prior processing steps. It is important to notice that the most significant failures of warning communication take place in the stage of capturing attention and encoding (Ho et al., 2006; Wogalter, Conzola, & Smith-Jackson, 2002).

As discussed in section 2.1.1, according to ISO/TR 16352 (2005) a warning should contain the following elements: an urgency, a reason, a consequence if not observed and instruction for action. The **urgency** is a fundamental element, which helps the receiver to attend to the warning and can facilitate and intense the driver's response (ISO, 2005). Furthermore, for the dynamic context of driving, a hazard always has a location which may change over time, e.g. a hazardous car in motion. Thus, a warning should also include an element for the **hazard direction** that helps to orient the driver's attention to potential hazards. This step is very important because a fast recognition of hazards can also facilitate the further processing steps of the driver, e.g. information integration, anticipation and action responses. In the ISO/TR 16352 (2005), the effectiveness of spatial warning cues is also discussed but they are not defined as key elements for warnings. The warning element of possible **hazard consequences** may not be required for many critical driving situations, especially if the warning contains the elements of hazard direction and **warning reason**. By providing these elements to the driver, e.g. communicating "a hazardous car is approaching from the right side", drivers should be able to anticipate possible consequences and may estimate the situational criticality through integration of environmental information. The element of **action instructions** is suited for fast driver responses like urgent braking or steering. Especially in these cases, drivers do not have enough time to think about the right actions. On the contrary, if drivers may have time to anticipate possible consequences of a critical situation, it is most likely that they will choose the right action, even if the warning does not contain the element of action instructions. Table 2.1 shows the integration of these considerations to recommended warning elements (ISO, 2005).

Table 2.1: Warning elements according to ISO (2005) and their adaption to ADAS warnings.

Warning element according to ISO	Adapted warning elements
1. Element which attracts attention	1. Urgency
2. Reason	2. Hazard direction
3. Consequence	3. Hazard cause
4. Instruction for actions	4. Instruction for actions
	5. Consequences (optional)

To describe the effects of each warning element, it is useful to discuss them in the context of the warning process. One important question is which element mainly affects which processing step on the warning receiver side. Figure 2.2, illustrates the integration of warning elements to the warning process model. I developed this integration after associating empirical findings to human spatial attention (see section 2.3.3) as well as theories to behavioral control and anticipation (see section 2.2) to the warning elements and warning process.

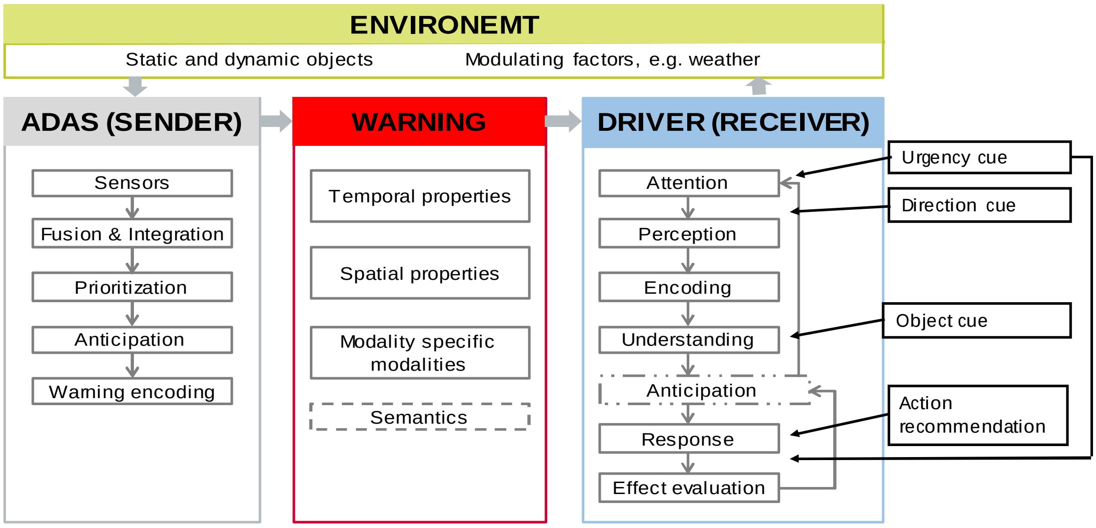


Figure 2.2: Illustration of warning elements applied as warning cues to processing steps of the integrative warning process model.

Figure 2.2 shows the adapted warning elements applied as warning cues to the integrative warning process model. An **urgency cue** will alert the driver and assist him to attend to the warning and modifies the intensity of the driver's response. Section 2.3.1 will describe which warning intensities are appropriate to alert drivers in connection with auditory perception. Furthermore, section 2.4.2 illustrates examples to the associated HMI design. The **direction cue** can orient the driver's attention to a hazard or relevant location and thereby facilitate the perception and following processing steps. The effectiveness of directional cues to direct the driver's attention and facilitate his responses has been proven in many lab and driving simulator studies. These findings and the associated requirements of the human perception and processing are discussed in section 2.3. The **object cue** can help the driver to understand the cause of the warning and to anticipate possible consequences. At last the **action cue** will assist the driver to choose the right action for his or her hazard response, especially in time critical situations. On the contrary, for early warnings, it is very probable that the driver will choose the right action response, even if the warning does not contain an action recommendation. For these scenarios, drivers should have enough time to choose the right action by evaluation of environmental elements and anticipation of possible effects. Section 2.2 will discuss the driver's behavior and the role of anticipation for critical driving scenarios.

A lot of research regarding ADAS warning cues and driving has been conducted for very time critical warning scenarios (see section 2.5). For these scenarios drivers usually have to respond as fast as possible. Little is known about the effects of specific warning elements for early warnings, where drivers have more time to respond to a warning signal. Especially early warning direction cues may assist drivers in attending to distant hazards. Moreover, early warning object cues may assist drivers to anticipate possible hazard effects. Thus, this thesis focuses on the effects of the discussed warning elements regarding upcoming warning ADAS with an extended sensory horizon (see section 2.4.3).

2.1.3 False Alarms and Unnecessary Warnings

A very important factor for all kinds of warning systems is the warning reliability. Very few people would respond to a warning, which usually turns out as a false alarm. In the context of ADAS warnings, false alarms play a major role for the effectiveness of a warning system. Beside the false alarms, there are also nuisance warnings and unnecessary warnings, which can negatively affect the driver's behavior and ADAS acceptance. **False alarms** are alerts that are triggered in the absence of an appropriate stimulus. For example, a false alarm occurs when a Frontal Collision Warning is broadcasted to a driver and there are no cars in front of the driver's vehicle (Campbell et al., 2007). In contrast to that, an appropriate stimulus is present for **nuisance warnings** but the warning is perceived as inappropriate, e.g. due to bad timing or poorly adapted warning intensity (Campbell et al., 2007). **Unnecessary warnings** occur, if an object is classified as hazard and the driver is alerted, but with proceeding driving situation the possible hazard turns out as a neutral object (e.g., Schmidt, 2012). Because unnecessary warnings usually are perceived as inappropriate, they represent a special case of nuisance warnings. The reliability of an automated situation-hazard-analysis and the associated warning timing mainly determines the ratio of unnecessary warnings. In this thesis I will examine the effects of false alarms and unnecessary warnings in the context of early warnings and discuss their impact on an integrative ADAS warning concept.

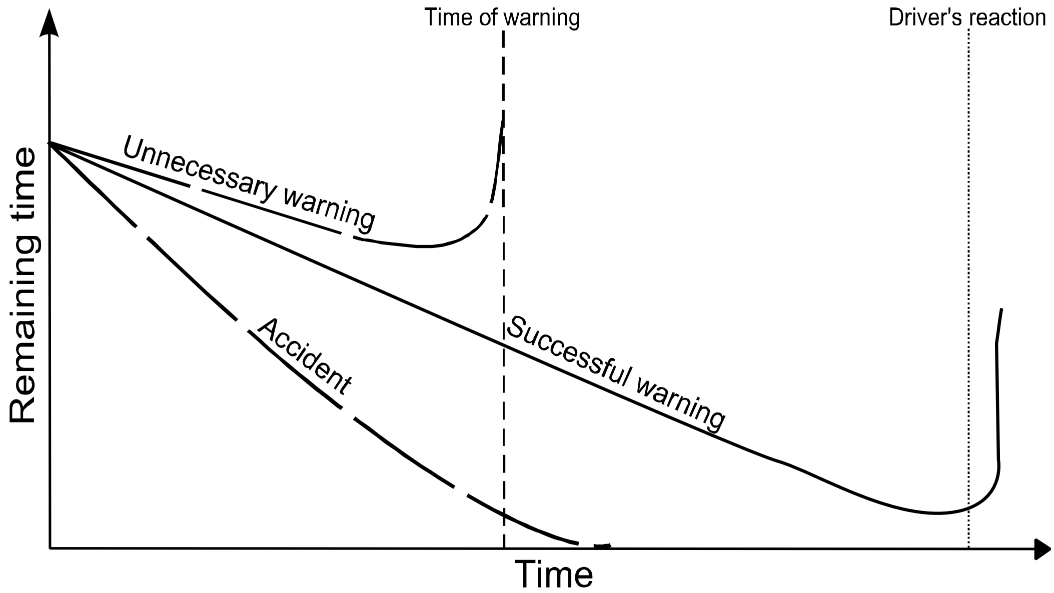


Figure 2.3: Time aspects of warnings from Kopf (1998) as shown in ISO/TR 16352 (2005). Time characteristics for successful warning, unnecessary warning and accidents are illustrated.

Timing is a key element in connection with successful warning. Figure 2.3 shows the remaining time regarding the progressing time for collision warning scenarios to illustrate the typical time profiles of successful, unnecessary and too late warnings. A successful warning has the right timing to alert the driver and offer him enough time to respond to a certain hazard. After the driver responded to the warning, e.g. a brake response, the remaining time increases. In contrast to that, an unnecessary warning is broadcasted before or while the remaining time increases because the possible hazard turns out as not critical. At last, for an accident scenario, the remaining time reduces successively and the warning is broadcasted too late. Thus, the driver has not enough time left to respond to the hazard. In the context of warning timing, an interesting point is, if early warnings are perceived as annoying or negatively affect the driver's behavior, especially if they are unnecessary. This question will be further discussed in connection with the second main study of this thesis regarding different HMI variants (see section 4).

To further explain warning reliability, the Signal Detection Theory (SDT; Green & Swets, 1966) is helpful. The SDT is used in many contexts and supports the process of decision making under conditions of uncertainty, e.g. the classification of potential hazards in traffic. When the SDT is applied to ADAS warnings, it classifies warnings by a 4-field matrix, see Figure 2.4.

	Situation warrants warning the driver (hazard present)	**Situation does NOT warrants warning the driver** (no hazard present)
Warning	True positive	False alarm
No Warning	Missing	Correct rejection

Figure 2.4: Classification of ADAS warnings according to the Signal-Detection-Theory adapted from Campbell et al. (2007).

In general, the SDT quantifies the ability to discern between signal and noise (e.g., Green & Swets, 1966). Regarding warnings, two factors determine the detection quality in the context of the SDT: the sensitivity (d') to discriminate a hazard in noise and the bias (β) that the receiver has a tendency to ignore or always respond to a warning. A high sensitivity helps the ADAS to identify a hazardous object in a group of many neutral objects (i.e. noise). An example for the bias is the crying wolf effect. It describes the bias of a receiver who is less likely to respond to a hazard because he experienced many false alarms before (Breznitz, 1985). As illustrated in Figure 2.4, four outcomes are possible according to the SDT: The hazard is present and a warning is broadcasted (true positive), the hazard is present and no warning is broadcasted (missing), the hazard is not present and a warning is broadcasted (false alarm) and the hazard is not present and no warning is broadcasted (correct rejection). Theoretically, a perfect warning system would have a classification of 100% true positives and 100% correct rejections, while the missings and false alarms stay at zero. Unnecessary warnings represent a special case regarding the SDT. The ADAS classify them as true positives, but in the course of the hazardous situation drivers recognize the wrong classification because the hazard has dissolved. Thus, there is incongruence between the classification of the ADAS and the classification of the driver. The perceived warning reliability of the driver is dependent on the ratio between all four hazard classification outcomes of the SDT (see Figure 2.4) and also of the congruency of the ADAS classification and his own classification, e.g. unnecessary warnings.

To adapt warning systems, the ratio between missing and false alarms can be adjusted by defining strict or liberal criteria for the hazard classification. For example, due to liberal criteria, the ADAS classifies nearly all objects as hazards, the probability of true positives increases and the probability of missing decreases. Furthermore, the probability of false alarms increases and the probability of correct rejections decreases. Thus, each criterion leads to a new ratio between the four hazard classifications outcomes.

In general, warning reliability has been reported to be one of the main factors that influences the effectiveness and acceptance of an in-vehicle warning system (Bliss & Acton, 2003; Cummings, Kilgore, Wang, Tijerina, & Kochhar, 2007). The warning timing and used HMI seem to moderate this effect (e.g., Naujoks, 2013). Even for a low ADAS warning reliability of 60% Naujoks (2013) could show comparable warning effectiveness as for a reliability of 100%, when a visual HMI was used. The implemented visual warnings contained direction cues and were presented in a head-up display. Furthermore, these early warnings were examined in urban collision scenarios with an onset of 2 s before the last possible warning onset. The effects of reliability were found for false alarms (no object) and unnecessary warnings (no critical object) regarding the number of safety critical situations (minimum TTA < 1 s) and a warning reliability of 60%. Additionally, drivers showed a significantly better performance for a warning reliability of 60% compared to a control group without a warning system. The study of Naujoks (2013) was the first study that examined the reliability of ADAS warnings in connection with early warnings for the urban context. The current studies will examine the effects of false alarms and unnecessary warnings based on the results of Naujoks (2013). In connection with an integrative warning approach, I will discuss how the HMI design may affect false alarms and unnecessary warnings, especially if an early warning onset is used.

2.2 Driver Model and Driver Behavior

In the following section I will define a driver model and discuss associated driving tasks which are relevant to critical driving scenarios. Then I will shortly explain the role of anticipation for driving and provide an overview of collision avoidance seen from the human point of view.

2.2.1 Driver Model

Regarding a driver model, it is essential to understand how the driver controls the driving action and how his behavior interacts with the vehicle and the traffic environment. Furthermore, it is convenient to discuss how warnings can assist the driving tasks. There is a broad agreement that the driving task can be described by means of the Model of Control Hierarchy (Janssen, 1979; Michon, 1971, 1985) which was modified by Donges (1982).

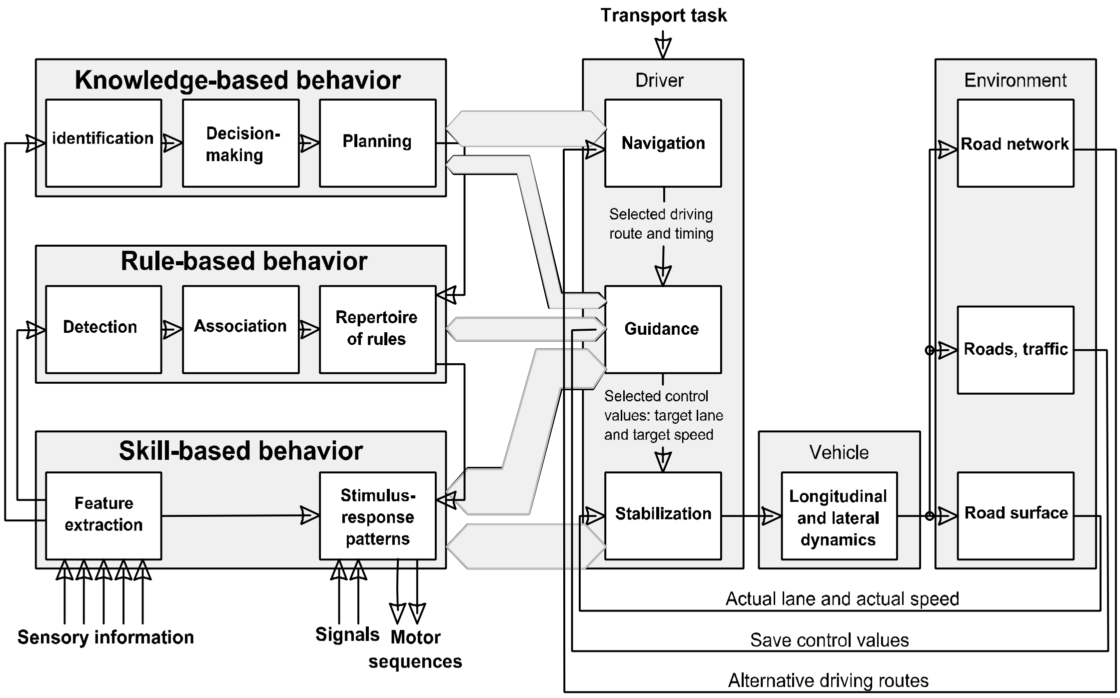


Figure 2.5: Combination of performance levels (Rasmussen, 1983) and Model of Control Hierarchy according to (Donges, 1982) published in Winner et al., (2009). Human performance levels are associated with driving task levels and organized in a hierarchical way. Furthermore, the driver and his car are in constant interaction with the environment.

The main elements of the integrative Model of Control Hierarchy are 3 performance levels according to Rasmussen et al. (1987) and 3 task levels of the driving (Michon, 1985), see Figure 2.5. The first performance level is **knowledge-based behavior.** This performance level describes behavior in situations in which stored rules cannot be applied, e.g. novel situations, and a plan must be developed to solve a problem. Thus, attentional resources must be allocated and decisions made. **Rule-based behavior** is controlled by learned sets of rules or procedures. Usually this behavior is controlled conscious and the control steps can be verbalized by the driver. **Skill-based behavior** is highly automated and controlled without conscious processes. The driver directly responds to features of sensory information and to salient signals (context cues) with automated motor sequences. In general, features which were extracted from sensory information are forwarded to all performance levels. These 3 performance levels are connected in a hierarchical order. For example, if a plan was made by the knowledge-based behavior, the single steps of the plan will be controlled by the rule-based behavior and carried out as response patterns of the skill-based behavior.

The first task of the 3 driving task levels is the **navigation task,** which corresponds to the decision where the driver wants to drive to and how long the trip should take. These decisions represent knowledge-based behavior and take longer than other driving tasks. The **guidance task** describes maneuvers, e.g. overtaking, turning or lane change. All three performance levels are relevant to perform maneuvers. However, rule- and skill-based behavior is mainly used to control different steps of a manoeuver. Furthermore, maneuvers can take multiple seconds and are consciously. In contrast, the **stabilization task** describes short driver actions like keeping the lane by steering. Most of these actions are performed skill-based behavior and take very short time, e.g. $t < 2$ s.

Similar to performance levels, the driving task levels interact in a hierarchical way. For example, maneuvers of the guidance task level are processed as single actions in the stabilization task level, e.g. overtaking by steering and hitting the accelerator pedal. After the driver performs these stabilizations actions, the vehicle responds with its specific longitudinal and lateral dynamics, which lead to a new vehicle position in the environment. The driver environment of the Model of Control Hierarchy is based on the road network which include roads, traffic and specific road surfaces (Winner et al., 2009). In a feedback loop, the vehicle position interacts with the environment and leads to new driving tasks. For example, driving over bad road surface, e.g. black ice or obstacles on the roads, will lead to new stabilization tasks. In contrast traffic jams may trigger a new navigation task of the driver.

The performance levels of the Model of Control Hierarchy are mainly differentiated by the degree of automation, needed attentional resources as well as the involvement of consciousness and memory (cognitive resources). On the contrary, the levels of driving tasks are mainly divided by task requirements and the time to carry out specific tasks. In addition to that, the performance levels are associated with corresponding levels of the driving task and interact in a hierarchical way. In general the needed cognitive resources decrease with lower driving task and performance levels. To positively influence driving behavior, it is important to notice the degree of automation and attentional resources needed for specific tasks. Orienting the driver's attention and providing appropriate information can be useful for conscious and not complete automated task. For highly automated tasks, the presentation of familiar context cues is useful. In connection with early ADAS warnings, drivers should be assisted in the guidance driving task (needed time usually > 2 s), which is mainly determined by the detection of relevant information, the association of this information and the selection of appropriate behavioral rules. Thus, warning cues should aim at assisting drivers in the detection of hazards and the association with behavioral rules. The selection of these behavioral rules can be influenced by the driver's anticipation (see section 2.3.3). Considering the warning elements (see section 2.1.2), especially the warning elements of direction and urgency should help drivers to detect relevant information (rule based behavior step 1). Furthermore, warning object cues should assist drivers in selecting the appropriate anticipation which is associated with a specific behavioral rule (rule based behavior step 2 and 3). Warning direction and warning object cues were examined in the conducted studies of this thesis, also because of their relevance to assist drivers on the guidance level.

2.2.2 Anticipation and Behavioral Control

We have to **anticipate which effects are caused** by a specific action to interact goal oriented with our environment. Especially in the context of driving, there are many situations in which humans have to anticipate the result of their maneuvers (actions) and the effects of other road users. The anticipation of different effects allows us to choose the right action to achieve a desired consequence. According to the ABC-Framework (Hoffmann, 2009) and the "ideo-motor principle" (James, 1890; 2007), action selection and the motor output is determined by the anticipation of an effect. An experienced driver may anticipate different steps of a parking maneuver and thereby select the right angle and distances to fulfill it. To estimate the probability of different effects of an action, action-effects relations have to be learned. Hoffmann (2009) describes this as a primary learning process in his anticipative behavioral control (ABC) framework. Both intended and non-intended effects, which are contingently experienced as out-comes of an action, will be linked with the performed action representation. Additionally, the conditioning of action-effect relations to a specific context is considered as being a secondary learning process. A context in which a certain action repeatedly produced a specific outcome can address the conditioned action-effect relations and elicit the readiness to produce this outcome by this action again (Hoffmann, 2009). For the parking maneuver example, a corresponding context could be a parking lot with specific parking markings, which helps the driver to select the correct action-effect relation for parking.

Anticipations must be made in a highly dynamic environment in the context of driving. This means, drivers have to anticipate desired effects for their manoeuvers, but also the effects of other road users. Concerning parking example, this means, the driver has to anticipate different steps of his parking maneuver and also the effects of pedestrians or other vehicles which are approaching the parking place. To describe this “extended anticipation” the model of Situational Awareness (SA) is suitable (Endsley, 1995). The model of SA is based on three sequential levels of understanding: Level 1 is the perception of elements in the current situations, level 2 is the comprehension of the current situation and level 3 the projection of future status. Regarding the model of SA, a projection of future states is only possible if relevant aspects of the environment have been perceived and understood. Depending on the level of SA, drivers can decide which actions are suitable for achieving the desired behavioral goals. In contrast to the ABC-Framework, SA describes many factors and processing principles which can influence decisions and action selection. For example, expectations, workload and multiple factors regarding the human memory, e.g. experience, schemata and prototypes for specific situations, can influence the selection of an adequate action (Endsley, 1995). Assessing the state of SA during driving is not an easy task. Loud thinking may distract drivers and side tasks, which measure SA (e.g Rauch, 2009), only represent indirect measures. In the context of this thesis, I will not refer to the full model of SA according to Endsley (1995), because the interaction of different SA stages and associated cognitive elements is not accessible to the measures which I use for warning concept evaluation purposes.

In this thesis I will discuss anticipation in the context of the warning process. Therefore, I will use the following working definition for anticipation: Anticipation describes the prediction of the driver for his own behavioral effects and effects of his environment (traffic). Furthermore, the anticipation of these effects can help drivers to select an adequate action to a hazardous driving situation. Especially meaningful warning cues may assist drivers in their process of anticipation, e.g. warning object cues (see section 2.1.2).

2.2.3 Collision Avoidance

To analyze the driver's behavior in the context of collision avoidance, it is necessary to use time distance and reaction time measures. Time distance measures describe the time distance between a host vehicle and a relevant object. The **time to collision (TTC)** is an appropriate measure for longitudinal traffic. The TTC is the relative distance between two moving objects, e.g. host vehicle and a leading vehicle. Furthermore, the TTC is calculated through the division of the spatial distance of two objects (d) by the relative velocity of these objects: $TTC = \frac{d}{v_{rel}}$. For example, the TTC can be implemented for Frontal Collision Alert systems and is used to define time distance criteria for warnings or interventions. There is a high correlation between the TTC and Tau (T), which can be directly perceived by humans. Tau describes the relative rate of visual expansion of an object, while the observer moves (Goldstein, Irtel, & Plata, 2007; Schmidt, 2012). Humans are able to detect object velocities by analyzing Tau (Goldstein et al., 2007). Schmidt, Khanafer, & Balzer (2009) examined TTC based urgency assessments regarding a host vehicle which was approaching a lead vehicle. The host vehicle drove in different speed conditions, 80, 100 and 130 kph. The lead vehicle had differing relative speeds of -50, -30 and -10 kph. Participants had to push a button if they felt that the situation was dangerous. Regardless of the host vehicle speeds, participants pushed the button with a TTC about 3 s, yet, for the -10 kph relative speed condition, this TTC was slightly higher. Thus, even a TTC of 3 s can be perceived as dangerous, which represents a time distance that corresponds to an early warning in an urban environment.

In the context of warning time, it is important to know the latest time when drivers can be alerted to a hazard. Figure 2.6 shows an overview of the estimated onsets for warnings and driver braking responses in connection with the TTC regarding a host vehicle and an obstacle (Winner et al., 2009). The relative velocity is assumed to be constant for illustration purposes. The driver's reaction limit is defined with a TTC of 1 s and illustrated by the yellow area between the last possible warning onset (pointed line) and the associated braking response (dashed line). The shown warning onset and estimated braking onset increases linearly with the relative velocity because of the necessary braking distance. With a brake response before or at the dashed line, drivers will avoid a collision. The estimated values are valid under good conditions, e.g. high coefficients of friction (Winner et al., 2009).

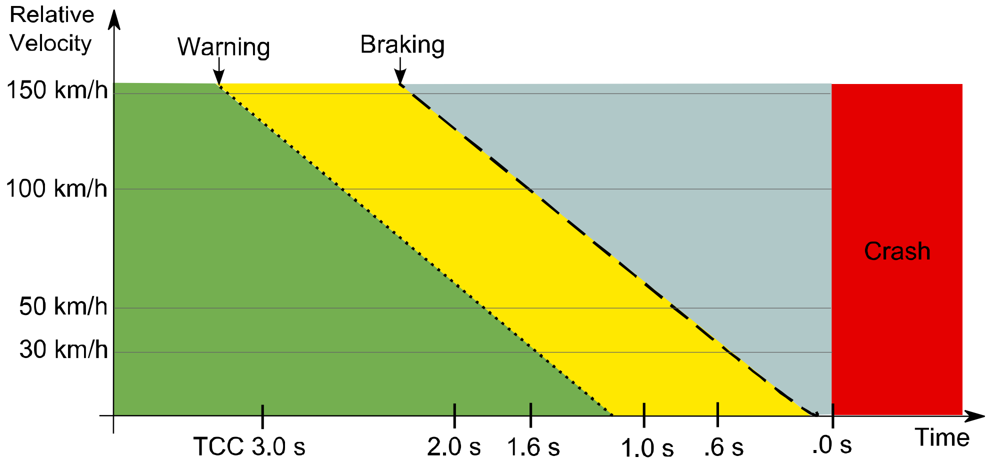


Figure 2.6: Illustration of estimated warning onsets and the associated time for a brake response in the context of the TTC between a host vehicle and an obstacle. The relative velocity is assumed to be constant for illustration purposes. The warning onset is defined with a driver latency of 1 s and increases linearly corresponding to the relative velocity (based on Winner et al., 2009).

Based on the last possible warning onset which is illustrated in Figure 2.6 and the findings of Naujoks, Grattenthaler, & Neukum (2012), see section 2.5, the warning onsets for the studies of this thesis were defined with 2 s before the last possible warning onset to cover an optimal warning onset for future C2X collision scenarios. These timings are described the in the context of each main study in section 3 and 4.

The **time to arrival (TTA)**, $TTA = \frac{d}{v}$, is suitable to describe time distances between an approaching host vehicle and crossing vehicles (Naujoks et al., 2013). The TTA is calculated through division of the spatial distance between the host vehicle and an approaching crossing vehicle (d) by the velocity of the crossing vehicle (v). The illustrated warning onsets of Figure 2.6 can also be applied to the TTA.

The TTC was used to calculate distances to frontal objects for the studies of this thesis, e.g. a leading vehicle, and the TTA for crossing objects at intersections, e.g. a car which approaches an intersection from the right side while the ego-vehicle also approaches this intersection. The TTC and TTA have a minimum of 0 s, which clearly indicates a collision. TTC and TTA values smaller than 1 s can indicate a possible collision (Hayward, 1972; Horst, 1990; Naujoks et al., 2013). Regarding these possible collisions, additional variables have to be evaluated to determine if a collision occurred and, if yes, how severe it was. Furthermore, the TTC and TTA can be used to define the timing of hazardous traffic and warnings for driving simulator studies (e.g., Naujoks, Grattenthaler, & Neukum, 2012).

To design and evaluate ADAS which assist driver in their braking reaction, it is important to consider how fast humans can perform braking reactions to a hazard. According to Young & Stanton (2007, p. 3) three elements of a braking response can be measured. The **brake reaction time (BRT)** is the time from presentation of the brake lights by the lead vehicle to the release of the accelerator pedal by the driver of the host vehicle. The movement time (MT) is the time from the release of the accelerator pedal to the depression of the brake pedal by the driver of the host vehicle. At last, the BRT and MT added together make up the total braking time (TBT). Many studies (see Table 2.2) have been comparing brake reaction times (BRTs) in the context of factors like host and lead vehicle speed, driver age and driver awareness. As illustrates in Table 2.2, depending on the study, BRTs were mainly measured in the range of 350 to 430 ms, MTs in the range of 170 to 180 ms and the TBTs in the range of 632 to 2450 ms. For aware drivers, the fastest reported TBTs were 550 ms (Schweitzer, Apter, Ben-David, Liebermann, & Parush, 1995) and for unaware drivers 650 ms. Very slow BRTs (4.2 to 6.2 s) were measured in conditions were lead vehicles decelerated slowly and did not illuminate their brake lights (Hulst, 1999). Warshawsky-Livne & Shinar (2002) showed that the age of driver affects the BRT. With increasing age, BRTs increase slightly, e.g. young drivers showed BRTs of 350 ms and old drivers BRTs of 430 ms.

Table 2.2: Summary of driver response times from the literature review for driver factors (Table adapted from Young & Stanton, 2007)

Condition	BRT (ms)	MT (ms)	TBT (ms)
Aware	4200[a]	180[b]	1300[c]
	360[b]		1290[d]
			550[e]
Partially aware	390[b]	175[b]	1100[c]
			632[d]
Unaware	6300[a]	170[b]	1360[e]
	420[b]		739[d]
			650[c]
Young	350[b]		2330[f]
Mid-age	390[b]		
Older	430[b]		2450[f]

BRT = brake reaction time; MT = movement time; TBT = total braking time. Note. The illustrated TBT is not equal to the sum of the BRT and the MT for each row because the individual values belong to different studies.
[a] van der Hulst et al. (1999); slow deceleration of lead vehicle without illuminating brake lights.
[b] Warshawsky-Livne and Shinar (2002).
[d] Sohn & Stepleman (1998); 85th percentile non-US data.
[e] Schweitzer et al. (1995); 50 mph (80 kph) with 12 m gap condition.
[c] Dingus et al. (1998).
[f] Warnes & Fraser(1993); no warning or distraction condition.

Regarding the definition of BRT, MT and TBT, some studies use another nomenclature, e.g. BRT as time until the brake is applied after a specific event. To increase clarity for my studies, I decided to use the term accelerator pedal reaction time to describe the time until the driver releases the accelerator pedal. Furthermore, I use the term brake reaction time (BRT) for the time until the brake is applied by the driver.

Kassner (2011) reviewed 14 studies that examined the effects of longitudinal warning ADAS and discussed that for all of these studies a warning system led to significant performance increase of the driver regarding the BRTs and the number of collisions. It is very likely that nearly all collision warning ADAS effectively assist drivers in their response to a hazard compared to a baseline without warning system. In this context, it can be more helpful to compare different ADAS warning variants regarding performance and acceptance, than comparing them to a baseline without system. Adapting this approach, the studies of this thesis compare different HMI variants for early warnings and analyze the associated brake responses.

2.3 Human Perception and Attention

In the following section I will describe the human perception and human attention in the context of driving and warnings with focus on stimulus intensity and spatial cues. These cues are main elements to help drivers to respond to a possible hazard. They have been explored in multiple time critical lab and driving studies, which highlight their relevance for the ADAS warning process.

2.3.1 Auditory Perception

For the design of auditory warnings that assist drivers effectively without startling them, it is helpful to illustrate the boundaries of the human auditory system. The intensity, the frequencies and many additional elements have to be processed by the auditory system to evaluate the quality of a sound. Humans are able to hear sound of frequencies between .02 kHz and about 16 kHz and sound pressure levels of 0 to 110 dB HL (Birbaumer et al., 2006). Figure 2.7 illustrates the human hearing threshold and the auditory pain threshold with associated sound pressure level and frequency level. The hearing threshold and auditory pain threshold are dependent on the frequency, thus very low or very high frequencies can only be heard with a higher sound pressure, e.g. x < .1 kHz or x > 10 kHz. The lowest hearing threshold lies between 2 to 5 kHz.

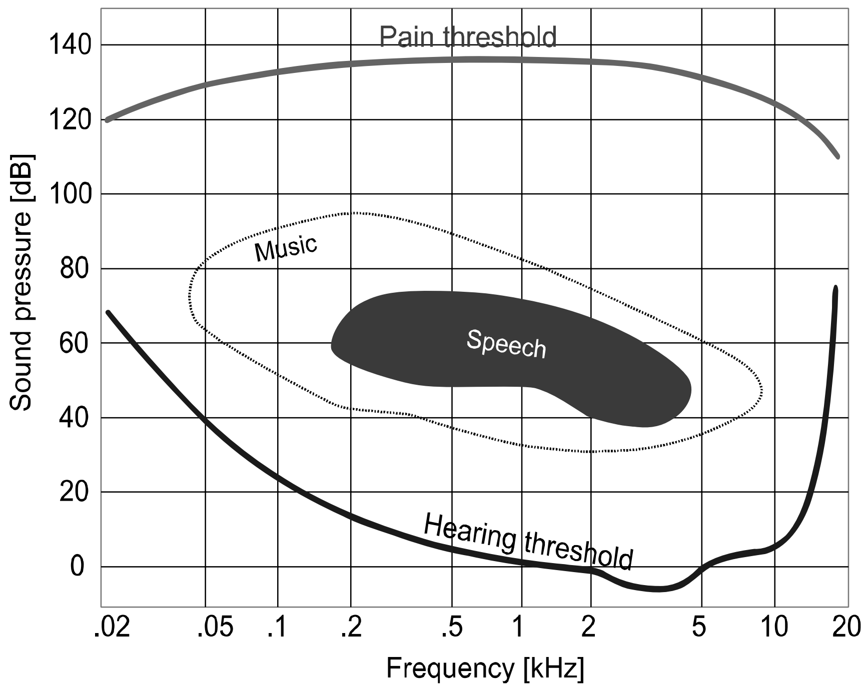


Figure 2.7: Hearing threshold and pain threshold of humans regarding the level of sound pressure and the frequency. Furthermore, the main frequencies and sound pressure levels to perceive speech and music are illustrated, based on Goldstein, Irtel, & Plata (2007).

If sound intensity exceeds the comfortable level, which is usually 20 dB below the pain threshold, it can trigger a Startle Reflex (SR). The SR is one of three mismatch reactions which are dependent on the stimulus intensity: an Orienting Reaction (OR) for mild stimuli, a Defense Reaction (DR) for intense stimuli and the SR for extreme stimuli (ISO, 2005). The OR is sensitive to new stimuli and can be habituated. With increasing sensitivity the OR can change into a DR or SR. The SR has developed to respond to harming stimuli by activating the autonomous nervous system and thereby get ready to “fight and flight” (Cannon, 1975). SRs can be triggered by stimuli of different modalities and are well documented for the auditory modality, e.g. SR caused by a pistol shot. In the context of warnings, SRs should be avoided because they can lead to unintended receiver behavior and bad acceptance regarding the warnings. Appropriate auditory threshold levels should be 15 – 25 dB (for planes) and 5 – 15 dB (for vehicles) above the regular noise level for the implementation of warnings (ISO, 2005; Patterson, Britain, & Authority, 1982). Besides, for many cases it is important to predefine or dynamically adjust the urgency of an auditory warning. To achieve this “urgency mapping”, different auditory parameters have been found to be effective, e.g. pulse duration, interpulse interval, alert onset, alert duty, frequency, speed change (Edworthy, 1994; ISO, 2005; Marshall, Lee, & Austria, 2007).

The auditory system of the human has to localize the sound source to effectively respond to spatial sounds. This localization process includes the determination of distance, azimuth and elevation of the sound source with the help of different auditory cues. Fricke (2009) provides an overview of different auditory cues and associated studies. She summarizes that sounds that have a wide frequency spectrum, e.g. include high and low frequencies, are easier to localize than sounds with a small frequency spectrum (Fricke, 2009; Wightman, Kistler, & Perkins, 1987). Furthermore, determining the azimuth of a sound source is easier than determining its elevation or its distance (Fricke, 2009).

In addition to that, Fricke (2009) showed that frontal and lateral sounds can be localized with an accuracy of 80 - 92%, for a classification tolerance of +/- 45°. By reducing this classification tolerance, the localization accuracy reduces dramatically, down to approximately 20% (Fricke, 2009). For sounds coming from rear, localization accuracies are much lower than for other spatial positions (Fricke, 2009; Thoma, 2010).

A good auditory warning should allocate the receiver’s attention and help him to localize a hazard with a comfortable sound intensity level. Furthermore, the auditory warning should use spatial cues and an urgency that corresponds to the associated hazard. For the auditory warnings of my studies, I chose a sound intensity of 75 dB which is in the comfort area, multiple frequencies which ease the sound localization, and an overall urgency that was adapted to the implemented warning scenarios (see sections 3 and 4).

2.3.2 Visual Perception

Visual perception is essential for the driving task. To process visual stimuli and understand their meaning, there are many steps of visual feature extraction, e.g. color processing, intensity processing, pattern recognition, 2D and 3D object integration, and also different association processes to associate semantics and to use visual cues. Because of the complexity of visual perception[2], I will shortly introduce a selected set of visual processing principles and visual depth cues, which are relevant to driving tasks and driving simulator studies.

The process of accommodation describes the adjustment of the shape of the eye lens to bring an image to focus on the retina (Birbaumer et al., 2006). Usually drivers visually fixate objects in middle distances with frontal view e.g. leading vehicles, curve tangents, traffic signs and parked vehicles. If drivers orient their gaze to the instrument cluster display or infotainment system of their car, their eyes will have to use accommodation to achieve clear vision. The binocular disparity describes the differences of an in-image object location resulting from the horizontal separation of the left and right eye (Goldstein et al., 2007). Disparity is a visual depth cue, which is especially effective in combination with visual motion cues and visual texture cues. If disparity is not available, time to contact estimations of drivers can be less accurate (Gray & Regan, 2000). "Optical flow is the distribution of apparent velocities of movement of brightness patterns in an image. Optical flow can arise from the relative motion of objects and the viewer" (Horn & Schunck, 1981, p. 185). The optical flow can be used by the observer to determine relative position changes and to detect if an object is moving (Goldstein et al., 2007; Schmidt, 2012). Thus, the optical flow can help to stay on course to the desired destination. Mourant & Thattacherry (2000) showed that the optical flow is associated with Simulator Sickness (see section 2.7). With increasing optical flow, caused by higher

[2]For detailed description of visual perception see Birbaumer et al. (2006) and Goldstein et al. (2007).

object density, e.g. more buildings and trees near the road, the probability for symptoms of Simulator Sickness increases.

The need of visual accommodation and the positioning of visual HMI elements will be discussed in section 2.4.2 (HMI devices) and in the context of the results of Study 2. Furthermore, the optical flow may be a main factor which determines the drop-out rate of participants in driving simulator studies and was especially considered for the design of Study 2 (see section 4).

2.3.3 Human Attention

Selective attention is highly relevant for the driving task and the processing of spatial warning cues. Selective attention describes the human process of selecting relevant information of the environment or the cognitive system to control specific, goal oriented actions (Müsseler, 2002, Chapter 1c; Zarife, 2010). This selection process aims at using the limited human cognitive resources optimally.

For the visual context, various studies showed that attention can be focused on locations, objects or features of the visual field (Müsseler, 2002, Chapter 1c; Posner, 1980; Rasmussen et al., 1987). For example, the spotlight metaphor (e.g., Posner, 1980) defines attention as a spotlight which can be oriented sequentially on different locations of the visual field and thereby facilitates the processing of relevant elements inside of the spotlight.

Regarding the usefulness of spatial warnings, results of the attentional **spatial cuing** paradigm are helpful. Posner (1980) could show that visual attention can be oriented by cues that are presented uni- or multimodal. Usually these cues indicate the position of appearing visual targets in the visual field. Additionally, these cues can facilitate the target perception and the associated behavioral responses. Posner (1980) demonstrated in different experiments that valid visual cues lead to response facilitation (called benefits) and invalid cues to response deceleration (called costs). Valid cues are cues that correctly predict the position of an appearing target stimulus. In contrast invalid cues falsely predict the position of an appearing stimulus. The ratio between valid and invalid cues mainly determines the effectiveness of spatial cues and can be compared to the reliability of warnings, see 2.1.3. In addition to that, spatial cues can be categorized by their kind of attentional processing. Endogenous cues, e.g. an arrow pointing towards a location, lead to “top-down” processing and a volitionally orientation of attention. In contrast exogenous cues, e.g. a simple line at the location of the appearing target, lead to “bottom-up” processing and a mostly automatic orientation of attention (Müsseler, 2002, Chapter 1c).

Spatial cues. For *spatial auditory cues* (sounds), a shift of visual attention to relevant visual areas and associated response facilitation could be demonstrated (Ho, 2004; Ho, Tan, & Spence, 2005). Thoma (2010) supports these findings, showing that responses to frontal, lateral, and rear objects (four 90° partitions) can be significantly facilitated by an auditory cue. In the context of driving simulator studies, it could be demonstrated that spatial auditory cues (warnings with direction) led to lower collision rates (Bliss & Gilson, 1998; Thoma, 2010). However, the initial reaction can be more appropriate for auditory cues without direction (Ho & Spence, 2005). Additionally, It seems to be effective to present the spatial cue corresponding to the direction of a hazard (Spence & Ho, 2008). *Spatial haptic cues w*ere also effective to assist drivers in attending to hazards, e.g. the haptic seat that uses different haptic zones (Fitch, Kiefer, Hankey, & Kleiner, 2007; Ho, Tan, et al., 2006). Regarding the presented studies on auditory and haptic spatial cues, the used spatial cues indicated the direction of a possible hazard by their own spatial location, which was not identical to the hazard location. Thus it is very likely that these cues represented endogenous spatial cues (usually processed top-down). However, but bottom-up processes may have been also involved to orient the drivers’ attention.

Ho & Spence (2009) conducted a lab study to examine gaze and brake responses regarding different warning signals (cues). In the lab study they compared close (40 cm) and far (90 cm) auditory warnings (“doo-doo,” modified from a phone ring tone, 15 ms on, 10 ms off, 15 ms on, 80 dB), a Velcro belt that applied vibrotactile stimuli to the stomach, and a baseline without warnings, see Figure 2.8. Participants had to respond to video scenarios that illustrated the sudden closing in on a heading vehicle until collision. As secondary task, the participants had to pull a hand paddle to indicate the color change of a LED-bar, which was placed 1 m right or left at about chest level when seated (Ho & Spence, 2009). The secondary task was used to orient the participant’s gaze to left and right. Then the different warnings were used to orient their gaze back to the critical driving scene. Moreover, auditory warnings were broadcasted from the direction to which drivers had to turn their head. As dependent variable, brake reaction times from warning onset until applying the brake were assessed. These brake responses were necessary because in selected trials participants had to respond to the sudden closing in on a heading vehicle.

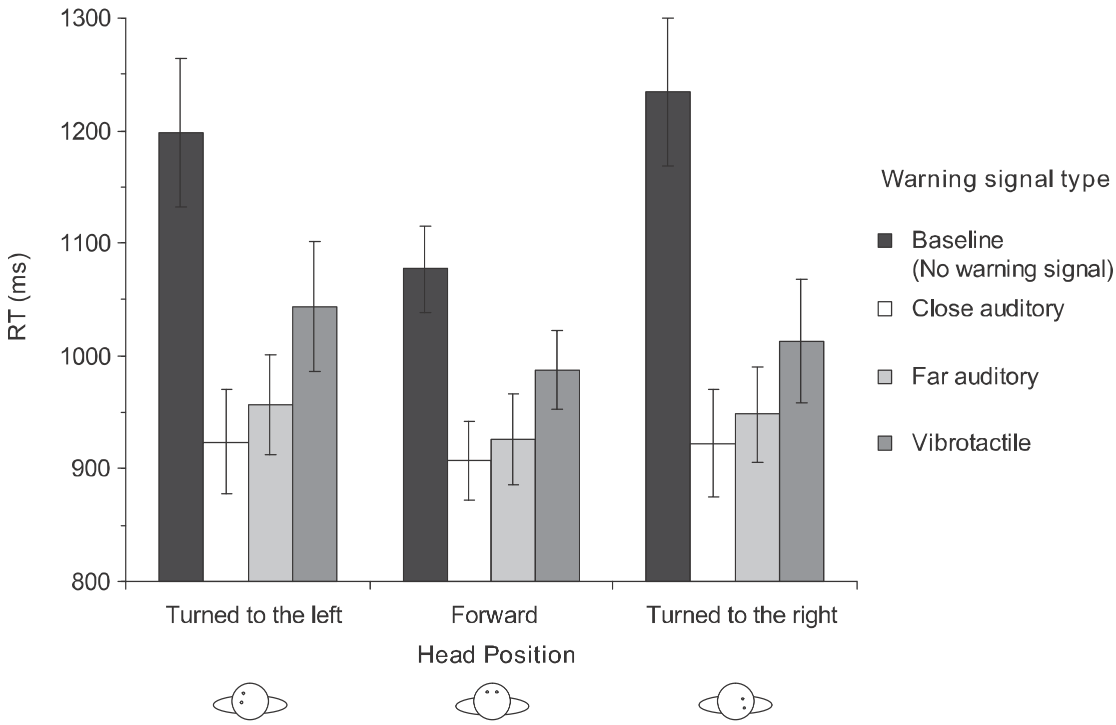


Figure 2.8: Mean brake reaction times as a function of the warning schemes and head position (Ho & Spence, 2009). Four warning schemes were used to orient the participants' gaze to a critical driving scene and to get them to initiate a brake response. The participants head position before warning onset was standardized to three directions: left, forward and right. All warnings facilitated the participant's response compared to the baseline without warning. The close spatial auditory warning was most effective.

The vibrotactile warnings were less effective than the spatial auditory warnings, but still more effective than no warning (baseline). Furthermore, close auditory warnings led to faster brake reactions times than far auditory warnings. Ho & Spence (2009) concluded that (spatial) auditory warnings cues appear to be effective in alerting and orienting a driver's gaze to the spatial direction with high relevance.

Regarding endogenous *visual spatial cues*, Posner (1980) could demonstrate their effectiveness in the spatial cueing paradigm (lab setting). In the context of driving simulator studies Werneke & Vollrath (2012) showed that especially early endogenous visual spatial cues (presented in a head-up display) were effective to avoid collisions at T-intersections, while late exogenous visual spatial cues were less effective.

Object cues. Posner & Snyder (1975a, 1975b) demonstrated that knowledge about a stimulus form can facilitate the attentional processing and associated responses to a target stimulus in multiple lab studies. Furthermore, Thoma, Lindberg, & Klinker

(2009) examined the effects of visual warning object cues (hazard icons) to assist drivers in their response to different hazards in a driving simulator study with late warning onset. However, the authors could not confirm the effectiveness of the visual object cues to facilitate driver responses to different hazards, but found positive effects for single scenarios (see section 2.5.2).

Spatial cues combined with object cues. Kingstone (1992) examined the interaction effect (combined expectancies) of spatial and non-spatial form cues (letters) in an orientation judgment task where participants had to press a key corresponding to the direction of a target stimulus (right or left). Kingstone found a significant RT delay when an unexpected stimulus form appears at an expected position, or an expected form appears at an unexpected position. According to Kingstone (1992), crosstalk between coding systems appears to underlie this interaction whereby information provided by the more rapidly resolved attribute (location) influences and inhibits the processing of the more slowly resolved attribute (form). The interaction effect can be eliminated by decreasing the validity of the spatial cues or by presenting a distractor stimulus at the position where no target stimulus is presented (Kingstone, 1992). These findings suggest that a combination of spatial and object cues is effective to orient attention to a target object, but only if expectancies about both cues are equally fulfilled.

Regarding the **driving task**, bottom-up shifts of attention are probable for salient elements, e.g. the red braking lights of a leading car may pop-out and trigger an attentional bottom-up process of the driver, which facilitates the necessary braking response. However, many attentional processes for the driving task are controlled top-down, e.g. the volitionally attending of the driver to objects and features like signs, traffic and road features (e.g., Schmidt, 2012). For most tasks of the driver it is quite likely that attentional top-down and bottom-up processes are used complementarily.

Findings on selective attention suggest that the driver’s attention and gaze can be oriented to relevant objects by (spatial) warning direction and warning object cues. Regarding ADAS warning integration, Study 1 of this thesis focuses on warning direction cues and Study 2 on the combination of warning direction and warning object cues to help drivers in directing their attention to a hazard.

2.3.4 Human Glance Behavior

The human glance behavior is an important measure to examine driver behavior. **Glance behavior** may not be a measure for visual attentional processes, but it is clearly correlated with visual processing (Huestegge, Skottke, Anders, Müsseler, & Debus, 2010). In the following I will shortly explain the main terms and parameters regarding the human glance behavior.

Saccades are consciously or unconsciously performed, fast eye movements, which can reach a velocity up to 700°/s and have a duration of 15 to 100 ms (Birbaumer et al., 2006). Usually they proceed stimulus fixations, but can also occur 2-3 times per second without a stimulus. The latency between visual activation and the beginning of a saccade takes about 200 ms. This latency decreases down to 70 ms for focused attention (Birbaumer et al., 2006). During a saccadic movement the visual perception is suppressed (Birbaumer et al., 2006).

Pursuit eye movements are conscious eye movements that follow visual moving objects with an accuracy of 1°. Their latency after visual activation is about 100 to 150 ms.

In addition, visual fixations describe the maintenance of the visual gaze on a specific location. They are proceeded by saccadic eye movements. In this context, the term glance is often defined as fixations within an area of interest. Typical parameters to analyze the glance behavior are the glance duration, the number of glances and total glance time. Besides, reaction times between an event and the fixation of a specific object can be analyzed. In the context of driving, Huestegge et al. (2010) showed that the visual scanning behavior, meaning the spatial distribution and number of fixations, differs between unexperienced and experienced drivers. Experienced drivers have learned which elements of a driving scene are most relevant for specific driving manoeuvers. Regarding the HMI interaction and driver distraction, the ISO (2005) illustrates the typical glance duration, number of glances and total glance time for different visual tasks of driving. Single glance durations for common tasks of the driver take about .4 to 1.6 s, and total glance times about .8 to 10.4 s including 1.2 to 7 number of glances. These values indicate that drivers have to shift their attention between the driving task (primary task) and for example elements of the infotainment system (secondary task).

Table 2.3: Glance durations, number of glances and total glance times for common task of the driver adapted from ISO (2005)

Device / Task	**Glance duration (s)**	**Number of glances**	**Total glance time (s)**
Turn an radio, find station, adjust volume	—	2 to 7	—
Radio (generally)	*1.2 to 1.3*	—	—
Left mirror	1.0 to 1.2	—	—
Speed (check or exact value)	0.4 to 1.2	—	0.8
Destination direction	*1.2*	1.3	1.6
Fan	*1.1*	2.0	2.2
Correct direction	*1.5*	2.0	3.0
Fuel range	*1.2*	2.5	3.0
Tune radio	*1.1*	6.9	7.6
Roadway name	*1.6*	6.5	10.4

Even if drivers are looking at relevant aspects of the environment, it is possible that they are not able to respond to them. This observation is often called looked-but-failed-to-see paradigm (Langham, Hole, Edwards, & O'Neil, 2002). For the looked-but-failed-to-see paradigm, sensory limitation and especially cognitive aspects like missing attentional resources and false driver anticipations have been identified as causative factors (Langham et al., 2002; Rumar, 1990).

In the context of ADAS warnings and critical driving situations, the driver's glance behavior can help to determine how effective warnings assist drivers to identify possible hazards, or to determine how distracting implemented warnings are. Therefore, the glance behavior was measured and results are discussed for both main studies for this thesis.

2.4 Advanced Driver Assistance Systems

Subsequently I will show an overview of ADAS and their classification. Then I will shortly describe HMI which can be used to alert the driver and the C2X technology, which highly increases the sensory horizon upcoming vehicles.

2.4.1 Classification

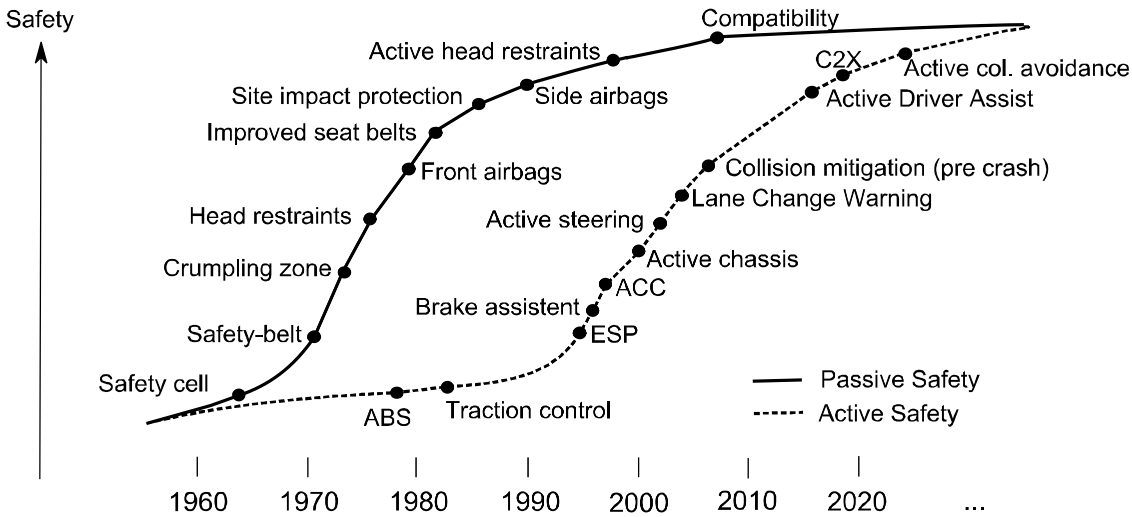
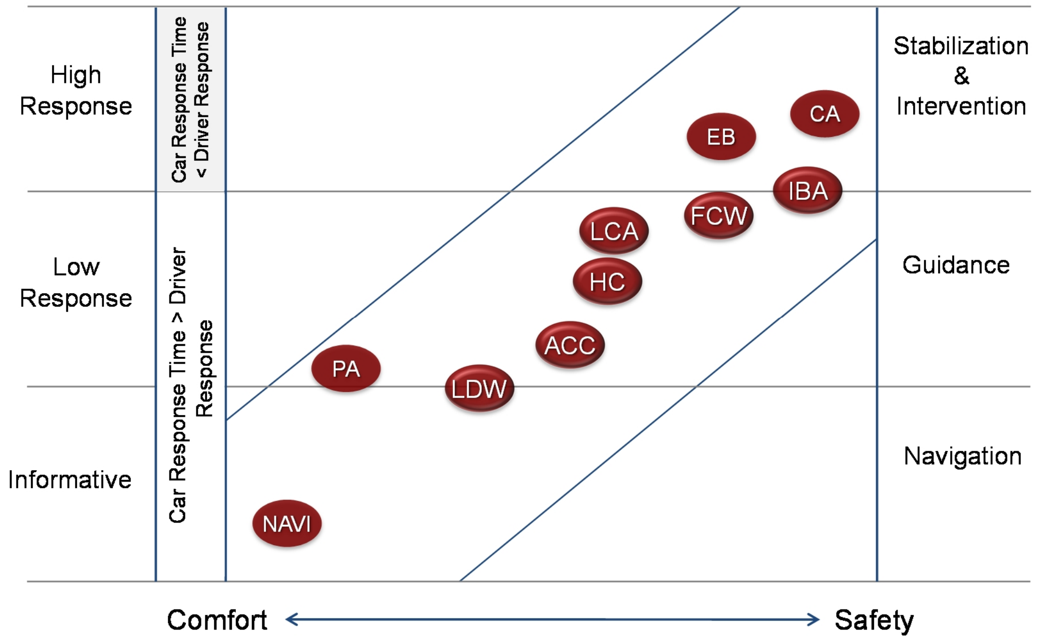


Figure 2.9: Overview of to the evolution of passive and active Driver Assistance Systems (DAS). Estimated, safety benefit increases over time due to the development of new DAS (DVR, 2006).

Figure 2.9 illustrates the evolution of Driver Assistance Systems (DAS) over time, divided into passive safety and active safety[3]. **Active Safety** systems actively influence processes of the driving task and have a high degree of interaction with the driver, e.g. the Adaptive Cruise Control with integrated Forward Collision Alert, which controls longitudinal driving and alerts the driver regarding frontal hazards. In contrast, passive safety system have a very fast response time and do not actively influence the driving task, e.g. the Active Headrest which automatically moves diagonally upward in a collision scenario and catches the back of the driver head. In this thesis I will focus on active

[3]For detailed description of the different Driver Assistance System see DVR (2006).

safety systems because of their great demands for the HMI design, especially regarding warnings, information and the usability of the input devices. The possible safety benefit, which is illustrated for each DAS in Figure 2.9, may be a rough estimation but it highlights the successive safety increment by the development of new DAS and ADAS.



Acronym	Description	Acronym	Description
ACC	Adaptive Cruise Control	IBA	Intelligent Brake Assistant
CA	Collision Avoidance (active)	LCA	Lane Change Assistant
EB	Emergency Brake Assistant	LDW	Lane Departure Warning
FCW	Forward Collision Alert	NAVI	Navigation system
HC	Heading Control	PA	Park Assistant

Figure 2.10: Overview of common ADAS classified by the driving task, the typical system response time and the safety benefit, based on Freymann (2006).

As illustrated in Freymann (2006), see Figure 2.9, ADAS can be classified by characteristics like their typical system response time and their corresponding driving task level, see driver model in section 2.2.1. Comfort and safety benefit are additionally applied as a bipolar dimension. According to Freymann (2006), ADAS with mid or high level of safety have got a short system response time and are placed at driver task level guidance and stabilization. In contrast ADAS with low safety and high comfort are placed on the driving task level of navigation and have got a high system response time. Fast responding ADAS are able to respond faster than the driver and work mostly autonomously on driver task level of stabilization. Freymann's illustration provides a good overview, but there is a lack of important factors for the ADAS clustering like system orientation and behavioral factors of the driver. Additionally, it is not necessary to define comfort and safety benefit as one bipolar dimension because there may be ADAS which lead to high safety benefit and also high comfort. A more driver centered ADAS clustering approach was made in connection with the German UR:BAN project (e.g., Petermann-Stock & Rhede, 2013), which examines the integration of upcoming ADAS for the urban context, see Figure 2.11.

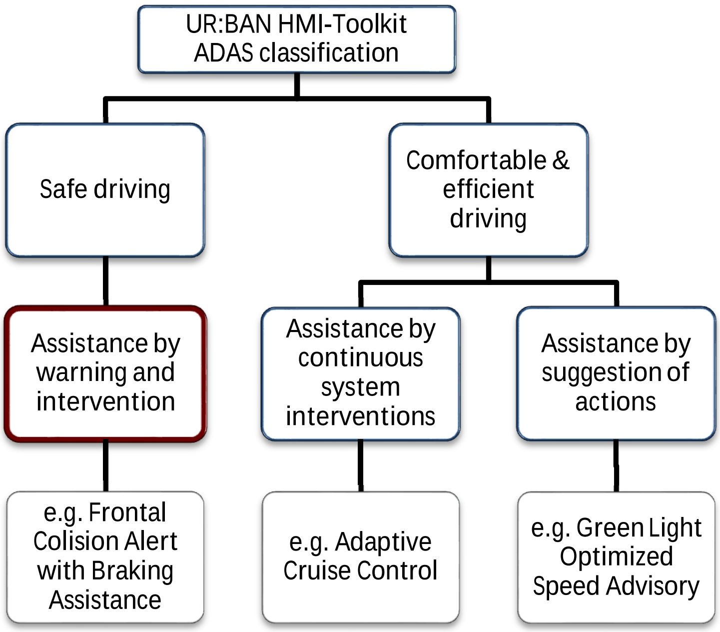


Figure 2.11: ADAS classification regarding the ADAS goal and HMI-function, based on UR:BAN MMI toolkit (Petermann-Stock & Rhede, 2013).

As illustrated in Figure 2.11, ADAS can be classified as systems that aim at assisting the driver regarding safe driving and systems that aim to assist the driver regarding comfortable and efficient driving. Usually, ADAS that assist drivers in safe driving use the HMI-strategy warning and intervention. For example, a Frontal Collision Alert System that includes Braking Assistance alerts the driver and assists him to initiate a braking response to a frontal hazard. The individual assistance strategies depend on the requirements of the associated use case, e.g. timing and criticality of the situation. In this thesis I will focus on warning ADAS, which can be assigned to the group "**assistance by warning and intervention**".

For ADAS of the second major group, which is called “comfortable and efficient driving”, two assistance strategies can be used: Assistance by continuous system interventions and assistance by suggestion of actions. For example, a “continuous system intervention” is used for the Adaptive Cruise Control, which continuously informs the driver about its availability and the system state. This is necessary because the ACC controls the longitudinal driving task and may not be ready to assist the driver with short interruptions due sensor limitations. The strategy to “assist drivers by the suggestion of actions” is especially useful for systems which aim at influencing the driver behavior in specific situations, e.g. the Green Light Optimized Speed Advisory suggests the driver to adapt his speed and thereby optimize the traffic flow in urban areas with many traffic lights (e.g., Rittger, Schmidt, Maag, & Kiesel, 2013).

As discussed in different studies (Lindberg et al., 2006; Thoma, 2010; Zarife, Schmidt, Kenntner-Mabiala, Metz, & Krüger, 2012), ADAS clusters[4] should consider behavioral factors like the driver’s response and the driver goal which are associated with the use cases of an ADAS, e.g. the driver’s response “braking” to avoid a collision (behavioral goal). These behavioral ADAS cluster-factors are easy to understand and to integrate into the mental model of the driver because they can be organized in a similar hierarchical structure like it is illustrated in the driver model, can address driver anticipations and are useful to define extendable ADAS clusters. In this thesis I focus on the ADAS cluster “Warning of collisions” which is a part of the ADAS group “warning and intervention” and associated with the behavioral goal braking and avoidance of possible collision.

2.4.2 Human Machine Interface

ADAS associated HMI devices can be grouped by their output modalities, see Figure 2.12. There are four main categories regarding these modalities: visual (e.g., head-up

[4] In a tabular analysis I examined 51 ADAS and found multiple ADAS clustering factors. For an overview of selected ADAS clustering factors see Appendix A.

display), auditory (e.g., warning tones), haptic (e.g., vibration on seat) and kinesthetic (e.g., the motion feedback while driving). As an example, Figure 2.12 shows subcategories of the auditory category like verbal or non-verbal auditory warnings.

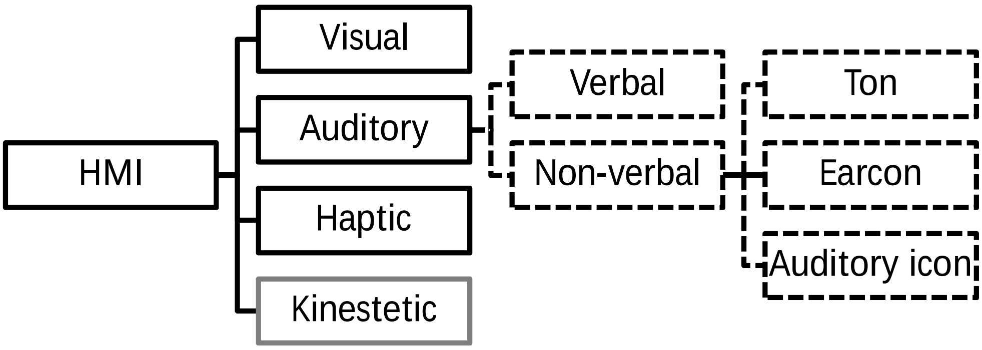


Figure 2.12: HMI classification regarding different modalities based on Jürgensohn & Timpe (2001). As an example, subcategories of the auditory category are shown in dashed rectangles.

Each modality has its advantages and disadvantages regarding a warning, e.g. an auditory warning may be less dependent on the location of occurrence than a visually warning. The main studies of this thesis will focus on auditory and visual HMI. For completeness, the haptic warning devices are also illustrated in the following.

Warning HMI for auditory modality. Auditory warnings are suited to attract attention for visually distracted drivers and to communicate few and short high-priority messages with low-complexity (ISO, 2005). In addition, they can be used discrete, sequential and also spatially-localized. Auditory warnings are broadcasted by the vehicle built-in audio system, which mainly determines the quality and modulation possibilities. For example, the spatial resolution and localizability of auditory warnings may be highly dependent on the quality of the used auditory system of the vehicle Thoma (2010). According to the ISO/TR 16352 (2005), warning can be classified into 4 main categories, see Table 2.4.

Table 2.4: Classification of auditory warnings adapted from ISO (2005)

Warning Type	Explanation	Example
Simple Tone	Single or grouped frequencies presented simultaneously	Square wave
Earcon	Abstract musical tones that can be used in structured combinations to create auditory messages. Sometimes referred to as complex tones	"Ding" or two-tone chimes
Auditory Icon	Familiar environmental sounds that intuitively convey information about the object or action they represent	Car horn or skidding tire sounds
Speech Message	Voice messages that add information beyond pure sound	"Danger"

A short, simple tone (e.g., 1000 Hz, 120 ms) with multiple repetition (e.g., 4 to 8) and short interpulse intervals (e.g., 80 ms) can be used as Frontal Collision Alert. On the contrary, earcons are usually used for less critical situations, e.g. a seat belt reminder. Auditory icons, e.g. the ring of a bike or the noises of a crash have been examined in multiple studies (Fricke, 2009) and were not found to be clearly more effective than tones or earcons. To use speech messages as warnings, it is useful to combine them with a visual component to ensure their meaning is perceived even in noisy situations.

There are many possibilities to map the situational urgency into a warning (see section 2.3.1). In general, auditory alerts should communicate a level of urgency, which is consistent with the urgency of the hazard (ISO, 2005). As discussed in the context of the warning process, spatial auditory cues can be used to orient the driver's attention and gaze to relevant objects and assist the driver in his response to a hazard (see section 2.3.3). Thus, auditory warning tones were implemented in both main studies of this thesis to examine the effect of warning direction cues.

Warning HMI for visual modality. In contrast to auditory warnings, visual warnings can communicate a high level of complexity, but may be easier to miss and are dependent on the location of the occurrence. Moreover, visual warnings can communicate spatial, temporal, discrete and continuous information (ISO, 2005). For highly critical driving situations, the exclusive implementation of visual warnings should be avoided because they can be missed by distracted drivers or they can catch the driver's attention too long. Thus, imminent visual warnings usually are combined with an auditory or haptic warning element. Visual warnings can be less annoying than auditory warnings because drivers can easier ignore them (ISO, 2005). Table 2.5 and Figure 2.13 show an overview of possible in-vehicle locations to present visual information to the driver. The windshield is suited for information that can assist the driver while performing the primary visual task, e.g. navigation information in a head-up display or visual warning cues presented by an LED-bar. The instrument cluster display is usually used for car status information, e.g. telltales, speed information, eco index, fuel information and warning symbols. In the last years, fully configurable cluster displays have been developed which can switch between visual themes that display elements like the speedometer and revmeter. The center stack display has enough space to show more detailed information like navigation, infotainment applications, e.g. navigation routes, tuning stations and rear camera view. Additionally, drivers may mount nomadic (bring in) devices like smartphones or tablets above the center stack of their car. Usually these devices are used for communication or navigation purposes. Locations near or inside the mirror can be used to show warning symbols or place LEDs to orient the driver’s attention to the mirror, e.g. blind spot warning with orange symbol in the right or left mirror.

Table 2.5: Possible in-vehicle locations to present visual information to the driver

	Location	Comment	Example
a, a2)	**Wind shield**	Primary field of view, no or few accommodation needed	LED-bar or head-up display position are illustrated in a2)
b)	**Cluster display**	Periphery to the primary field of view	Speedometer, Vehicle status, TSM-information
c)	**Center stack**	Periphery right to the primary field of view. Viewable for driver and co-driver	Navigation, Infotainment
d)	**Nomadic mobile devices**	Right to the primary field of view	Smartphone running a navigation software, mounted near the center stack
e)	**Rear mirror**	Periphery upper primary field of view	Rear view
f)	**Side mirrors or A-Pillar**	Left or right to the primary field of view	LED or Symbol for Blind Spot Warning

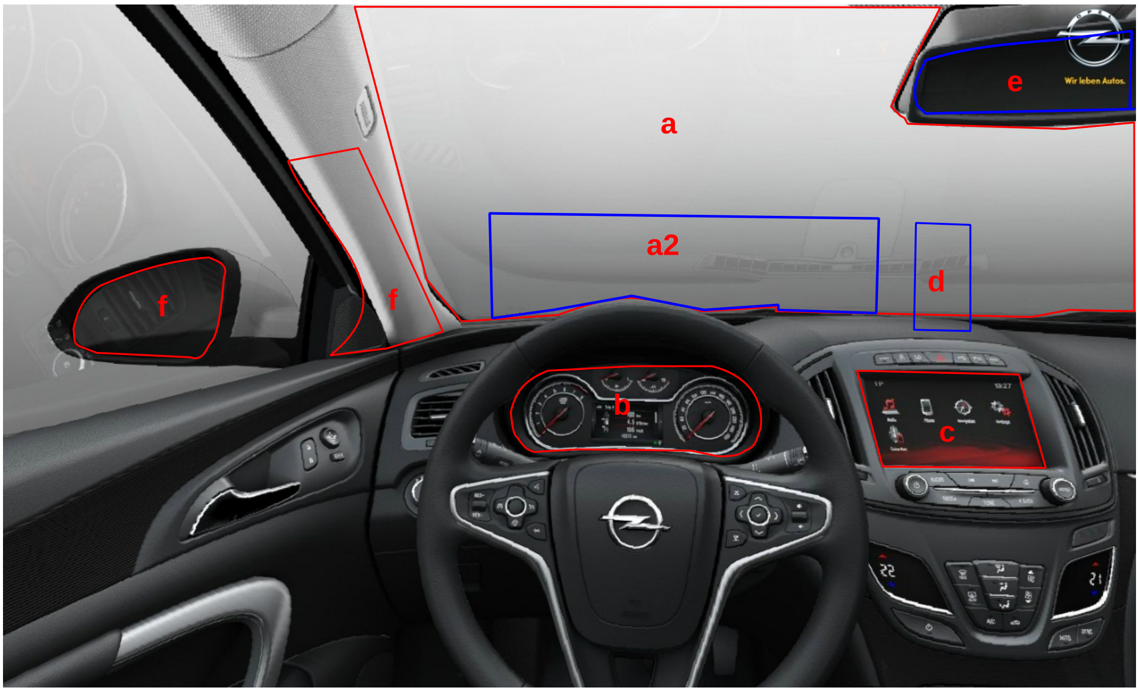


Figure 2.13: Exemplary interior driver view to possible visual areas of warning and information communications. The figure does not show an LED-bar (a2) or a nomadic mobile device (d) but illustrates their possible position in the driver Field of View.

To design visual warning HMI, the ISO (2005) provide additional, more detailed information, e.g. about the color coding, the text and symbol size, the display positions, and the allowed level of distraction. Because visual warnings can communicate complex information, they were used to implement warning object cues (hazard cause) in the main Study 2 in order to examine their effects regarding collision avoidance.

Warning HMI for haptic modality. Haptic warnings are suited to alert the driver in highly critical situations and actively assist him to initiate a response action, e.g. a torque on the steering wheel which should help the driver to steer back in his lane, see Table 2.6. Because haptic warnings can facilitate driver responses, but also influence the natural driver responses to a hazard, they should be evaluated carefully to identify possible unintended driver behavior. In contrast to auditory warnings, haptic warnings alert only the driver, and not his co-drivers, e.g. vibration on the driver seat. Thus, haptic warnings can be less nuancing. The haptic seat (e.g., Fitch, Kiefer, Hankey, & Kleiner, 2007) is a proven solution to provide spatial cues to the driver by vibration of multiple haptic zones. In this context Fitch, Hankey, Kleiner, & Dingus (2011) showed that a maximum number of three distinguishable alerts is recommended, when quick and accurate manual responses are required and additional alert modalities are not utilized. On the contrary, counter-torques are especially implemented in systems that assist drivers to keep their lane or prevent them from accidentally leaving the road. Active actuators can be used to provide drivers an action recommendation through counter-pressures, e.g. reducing speed or braking. In addition to that, active seatbelt tensioners can be used to alert the driver by short tensions of the seatbelt, e.g. as Frontal Collision Alert.

Table 2.6: Examples of haptic HMI

Haptic feedback	Example
Vibration	Haptic seat which alerts the driver by vibration on segments corresponding to the direction of a hazard
Counter-torque	Counter-torque on steering wheel that keeps drivers in their driving lane (Lane Keep)
Active actuators	Active accelerator pedal which applies counter-pressure if drivers should reduce their speed
Active seatbelt tensioners	An active seatbelt tensioner which shortly tensions the seatbelt to alert the driver against a frontal hazard

In my thesis I focus on auditory and visual warning HMI because the HMI for an integrative ADAS solution should also be available for small and compact cars without haptic seat. In addition, warnings of other modalities are also effective to help drivers in their perception and response to a hazard (see section 2.3.3).

Warning cascade. It can be useful to use a warning cascade which broadcasts multiple warning signals sequentially to alert the driver. The UR:BAN project (e.g., Petermann-Stock & Rhede, 2013) suggests a warning cascade that includes the following warning steps: A cautionary warning to alert the driver and catch his attention, a warning that may lead to a driver response, an imminent warning that must lead to a driver response, an intervention of the ADAS and a de-escalation which helps the driver to get back to the driving task. In general, these steps are a good approach to warning standardization, but also have to be evaluated in the context of each warning use case. For many use cases, the time of high confidence for the hazard classification may be so close to the warning that only one or two warning steps can be implemented. Furthermore, in order to examine driver responses to early ADAS warnings and the effects of single warning elements (see section 2.5) it is useful to focus on single warnings steps. After doing so in the studies of this thesis, I will shortly discuss the results in the context of warning cascade (see section 5).

2.4.3 Car-to-X Technology

C2X technology allows the communication between vehicles and the infrastructure, e.g. traffic lights, electronic traffic signs, and thereby **extends the sensory horizon** of C2X equipped vehicles. “Using C2X communication, warnings of potential risky situation are no longer limited to local detection only” (Stübing, 2013, p. 9). Instead dangerous situations are detected once and forwarded to approaching vehicles and their drivers. Thus, drivers are able to adapt their behavior early to possible hazards with the help of warnings and information coming from C2X (e.g., Stübing, 2013).

Car-to-X applications and associated use cases can be grouped into three categories: road safety related, traffic efficiency oriented and service oriented (Stübing, 2013). For this thesis, road-safety related use cases are most interesting because they are usually associated with driver warnings and driver information HMI. Typical safety related use cases are: Emergency Vehicle Warning, Intersection Collision Warning, Emergency Electronic Brake Lights and Stationary Vehicle Warning. For example, the Emergency Vehicle Warning informs the driver of a C2X equipped vehicle about the position and direction of an approaching emergency which activated its siren. This information can help drivers to initiate avoidance maneuvers and to respond to the approaching emergency vehicle. Additionally, the C2X Intersection Collision Warning can assist drivers to avoid lateral collisions at intersections. To reduce accidents as well as accident severity in an urban context, the Intersection Collision Warning is very important due to the high number of accidents occurring in intersection scenarios. For the conducted studies of this thesis, I focused on safety related C2X use cases which alert drivers early to avoid possible collisions.

2.5 Possibilities of ADAS Warning Integration

In the following section I will explain the differences between warning prioritization and warning generalization. To examine how integrative ADAS warnings can be made easier to understand for the driver, I focus on generalized warnings. Generalized warnings also address the central question, which warning elements should be included in an ADAS warning. This question often has been examined under the term “warning specificity”. In this context I will provide an overview of available findings and highlight the need for further research.

2.5.1 Warning Prioritization and Warning Generalization

Warning prioritization is a main approach to evaluate warning messages and to decide which of them must be broadcasted and which can be suppressed in the context of ADAS warning integration. Therefore the urgency and criticality of each warning use case have to be evaluated. Campbell et al. (2007) suggest a prioritization process which needs at last 5 examiners. Their main task is to assess the urgency and criticality of each warning use case and its associated warning message. After the rating process, a prioritization list can be created and finally reviewed by the examiners. Usually these lists are implemented in an ADAS warning prioritization algorithm in order to decide which priority is assigned to which warning. There have been multiple approaches which dynamically adapt warning priorities to the situation context and driver state to improve warning prioritization, e.g. if the driver is distracted, a warning is broadcasted earlier or more intensive (Amditis, 2010). Another possibility to improve warning integration and prioritization is the usage of **generalized warnings** (also known as generic warning or master alerting). Generalized warning approaches aim at using the same warnings for multiple use cases and ADAS, and thereby reduce the number of different warning signals. It is important that generalized warnings are used for clusters of ADAS use cases, which have similar requirements, e.g. a warning message for all highly critical collision scenarios (see section 2.4.1). From the driver's perspective, this approach can be an improvement because he has to understand less warning signals and also may easily integrate use cases of specific ADAS clusters into his mental model (e.g., Lindberg et al., 2006). Furthermore, for warning prioritization, it can be easier to prioritize ADAS clusters and then subsequently single use cases. Generalized warning signals are also suited to examine which warning elements have to be communicated to the driver (often called warning specificity). Because this covers one of the central questions which were discussed in the context of the warning process (see section 2.1.2) I will focus on warning generalization, especially in the context of early warnings.

2.5.2 Warning Specificity and Associated Empirical Findings

To examine warning generalization, it is necessary to vary the **warning specificity** (Naujoks, 2013; Thoma, 2010). A very specific warning, e.g. a warning which shows a pedestrian symbol, cannot be used for a hazardous vehicle scenario. Thus, it is necessary to use more generic (generalized) warnings for multiple use cases.

Generic warnings are based on a reduction of specific warnings and thus a reduction of information. An example for very specific warning could be a specific tone combined with a specific symbol for a laterally approaching bike, see Figure 2.14. In contrast, a maximum generic warning would be a “Master Alert”, e.g. auditory tone, for all emerging hazards. Between these two extremes semi-generic warnings can be used, e.g. a warning for all kinds of collisions.

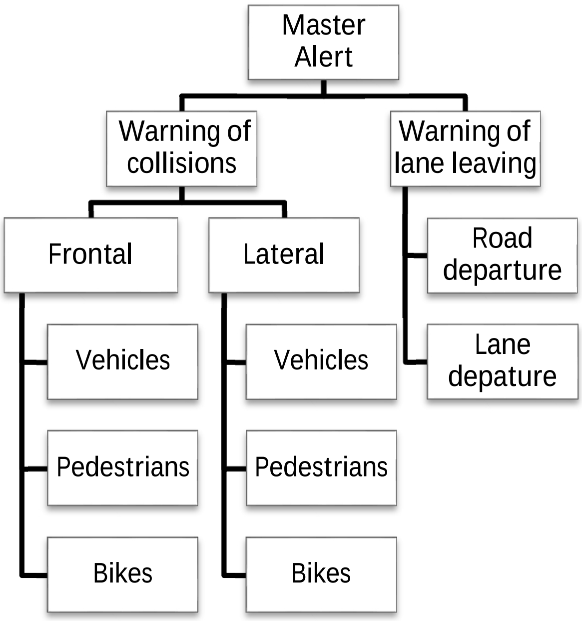


Figure 2.14: Example for different levels of warning specificity. The Master Alert represents a complete generic warning which is used for all use cases. By following down the branches of the warning tree, the warning specificity increases. Thus, a very specific warning would be a distinguishable collision warning of a laterally approaching bike.

Because generic warnings usually contain only single or few warning elements, they are suited to examine the effects of single warning elements, e.g. urgency or (hazard) direction (see section 2.1.2). In the past few years, few driving simulator studies have been conducted which examined the Master Alert and generic warnings in the context of ADAS (Cummings et al., 2007; Herzberg, 2012; Naujoks, 2013; Naujoks et al., 2012; Thoma, 2010). Studies (Cummings et al., 2007; Thoma, 2010) which examined the Master Alert in the context of different ADAS use cases, mainly focused on time critical scenarios (late warnings). These studies did not find negative effects of the Master Alert on the driver performance compared to more specific warnings. At the first sight, these findings may suggest that only very few ADAS warning elements are sufficient to alert the driver. However, taking a closer look, there are certain validity limits of these findings. These studies do not directly cover early warning onsets or report the effects of warning specificity on the warning acceptance of the driver. On the contrary, recent studies of Naujoks (2013; Naujoks et al., 2012) examined the warning specificity of early ADAS collision warnings (different scenarios) and found positive effects of visual hazard direction cues on the situational criticality and warning acceptance. The warning timing and the kind of HMI implementation seem to be key elements to answer the question which ADAS warning elements are needed to effectively alert drivers and to ensure the warning acceptance. Effects of late warnings cannot be transferred to early warnings because the driver has more time to process the warning and assess the situation, e.g. more time for anticipation and action selection. Thus, I will focus an early ADAS warning, which have been little examined, and analyze the effects of warning specificity (warning elements) on performance and acceptance. In addition, I will also take into account possible effects of warning specificity on false alarms and unnecessary warnings (see section 2.1.3), which have been recently highlighted by Herzberg (2012).

In the following I will describe the mentioned studies which analyzed warning specificity in the context of ADAS warnings. These studies, mainly focused on the questions of whether generic ADAS warnings lead to poorer driver performance or less ADAS acceptance than more specific ones.

Master Alert studies with late warning onset. Cummings et al. (2007) investigated the effects of a Master Alert in auditory modality. The authors used a fully instrumented, fixed-based driving simulator and an experimental manipulation of Warning scheme (generic, specific), Warning reliability (low, high) and Collision type (FCW, LDW, FVFA). Furthermore, Warning scheme did not affect response times and response accuracies, indicating that the generic warning approach was equally effective as the specific warning approach. In contrast, the collision type and especially the warning reliability affected response times and response accuracies. The specific warnings were associated with individual collision types and could be distinguished through a specific tone pattern: four-pulse-tone, two-pulse-tone and left/right directed, repeated rumble patterns.

Thoma, Klinker, & Lindberg (2008) investigated the effects of a Master Alert for six representative intersection assistance systems in auditory and visual modality. The examined ADAS (uses cases) were: Forward Collision Warning (FCW), Cross Traffic Warning (CTW), Oncoming Traffic Warning (OTW), Pedestrian Warning (PW), Red

Traffic Light Warning (TLW), and Stop Sign Warning (SW). The authors used a static driving simulator (180° view, BMW mockup) and video scenarios to manipulate Warning-cause detectability (low, high) and Warning specificity (auditory only, auditory and generic icon, auditory and specific icon). The results showed that a generic warning approach (auditory and generic icon VS auditory and specific icon) did not lead to slower braking reaction times than specific warnings. One exception was the red traffic light warning at low warning-cause detectability. A coherent influence of situation complexity indicated that specific warning icons may be more valuable in situations where the cause of warning is not perceivable (Thoma et al., 2009).

Generic warnings with early warning onset. Naujoks, Grattenthaler, & Neukum (2012) examined ADAS warning specificity through manipulation of Warning direction (no direction, with direction) and Warning object (no object, with object) for three urban driving scenarios. They also compared two warning onsets: The last possible warning onset (t_0) and two seconds before that (t_{0+2s}). To emit the visual warnings, a head-up display was implemented. For scenarios with cross traffic, warning with direction led to lower situational criticality and higher warning usefulness ratings than warning without direction. “Warning object” had no effect on the situational criticality and the warning acceptance. Furthermore, the early Warning onset (t_{0+2s}) led to lower situational criticality and higher warning acceptance than the late one (t_0).

The bachelor thesis of Herzberg (2012) compared specific (direction cue), specific false (false direction cue) and generic (no direction cue) warnings which were visually displayed in a head-up display and alerted drivers to C2X intersections scenarios. The specific and the generic warnings were rated more useful and led to greater distance to hazards, than the specific false warnings. Specific and generic warnings did not differ. Herzberg argues that low warning reliability leads to very poor warning acceptance and thus has to be considered, especially in relation to specific warnings.

Regarding the presented empirical findings to warning specificity and integrative ADAS warning approaches, it has to be further examined how warning specificity affects the driver's behavior for an early warning onset. Therefore the effects of early warning direction cues and warning object cues should be analyzed in detail, i.e. main effects and interaction effects of direction cues and object cues on the driver behavior. Besides, available studies did not clearly compare frontal and pronounced lateral warning scenarios. Drivers may profit from warning direction and warning object cues for their response to a hazard especially in lateral warning scenarios. Additionally, there is a lack of studies that analyze the driver's gaze behavior in combination with the driver's braking behavior for early warnings. At last, existing studies indicate that warning specificity affects the warnings acceptance, especially for unnecessary warnings and false alarms. These findings have to be further explored for an integrative ADAS warning approach regarding different collision warnings and associated false alarms and unnecessary warnings.

2.6 Research Questions

To examine warning cues the in the context of ADAS warnings It is necessary to manipulate the warning specificity. This means that effects of single warning cues can be assessed and compared to warnings which contain other single warning cues or multiple warning cues. Warnings which only include single warning cues are more generic and can be used for multiple use cases, e.g. a warning that only includes an urgency cue and is used for nearly all hazards (called Master Alert; see section 2.5.2). Generic warnings may be easy to understand for the driver, because they minimize the learning effort which is needed for multiple specific warnings. Furthermore, generic warnings may be easy to prioritize, if they are associated with ADAD use cases that have common factors from human and technological perspective (see section 2.4.1). For an integrative ADAS warning concept, it is necessary to know if generic warnings can be implemented for multiple use cases. For this work I focus on the ADAS subgroup “warning of collisions” of the ADAS cluster warning and intervention because the associated use cases offer similarities for the driving level (e.g., guidance and stabilization) and the typical driver response (e.g., braking; see section 2.4.1).

In the context of the warning process (see section 2.1.2), the first warning cues to examine are the warning urgency and the warning direction cue. These cues can assist drivers in their attentional processing and thereby can facilitate their responses to possible hazards. In the next steps, warning object cues have to be evaluated, because they can assist drivers to anticipate possible hazard effects (see section 2.1.2 and 2.2.2).

Many studies (e.g., Desimone & Duncan, 1995; Ho, 2004; Ho & Spence, 2009; Posner, 1980; Spence & Ho, 2008) showed that spatial and symbolic object cues of different modalities can be used to direct participants gaze and attention, see 2.3.3. Only few studies examined these warning cues in the context of ADAS warning specificity (e.g., Cummings et al., 2007; Herzberg, 2012; Naujoks et al., 2012; Thoma et al., 2009). Furthermore, nearly all of these studies focused on late warning onsets (except Herzberg, 2012; Naujoks et al., 2012, 2013), and the question remains if effects of late warning onsets can be transferred to scenarios with early warning onsets. Early warnings to collision will be made possible through upcoming C2X technology and improving sensors (see section 2.4.3), and thereby represent a central point for an integration approach of upcoming warning ADAS. Thus, a main question of this thesis is, whether lab study findings to attentional cuing and findings to warning specificity can be applied to different hazardous warning scenarios with early warning onset. The warning timing is a central point for warning processing. Early warnings (more time to respond hazards) may lead to other effects on the driver behavior than late warnings. Additionally, for scenarios with lateral hazard, drivers have to orient their attention to the right or left and may profit more from an early warning direction cue or object cue than for frontal hazards.

Beside the effects of warning specificity on driver performance, I will also examine possible effects of warning specificity on the ADAS system acceptance and the desire to buy these warning systems. As the studies of Naujoks et al. (2012) indicate, especially early warnings with direction cues can reduce the situational criticality and may improve the system acceptance. Furthermore, false alarms and unnecessary warnings can negatively influence the warning efficiency and acceptance (see section 2.1.3), and interact with the warning specificity (e.g., Herzberg, 2012). In this context, it has to be further explored which warning elements are most important for warning acceptance, and how they exactly interact. Thus, the studies of this thesis will take into account the effects of warning specificity on warning system acceptance and the desire to buy warning ADAS, for warning scenarios, false alarms and unnecessary warnings.

Regarding the method, I decided to conduct my studies in the driving simulator to analyze how warning specificity of early ADAS warnings affects driver behavior and ADAS acceptance. The main reasons therefore were the possibilities to use standardized, critical scenarios without harming participants in case of a collision. Furthermore, the driving simulator offers the option to use techniques like occlusions and adaptive traffic flow to time and standardize the driving scenarios and warning onsets.

Main Questions

To examine effects of specific warning elements in the context of early warnings and ADAS integration, I focus on the following main questions for this thesis which were examined in two main studies:

- Do drivers benefit from a warning direction cue and/or a warning object cue for their hazard response in the context of early ADAS warnings? Study 1 focused on a warning direction cue and Study 2 on a warning direction cue and/or a warning object cue.
- Is a possible warning specificity effect more pronounced for lateral warning scenarios than for frontal scenarios? Both main studies compared frontal and lateral scenarios in the context of the warning specificity.

- Does warning specificity affect the warning system's acceptance and the willingness to buy new warning ADAS, especially if false alarms or unnecessary warnings are considered? Regarding this question, Study 1 focused on false alarms and Study 2 on unnecessary warnings.
- Is an ADAS cluster, which covers ADAS of the group "warning of collisions", suited for warning generalization? Both studies investigated generalized warnings for different ADAS use cases.

In the first main study, I examined how early warning direction cues affect driver behavior and ADAS acceptance in a rural setting regarding frontal scenarios, lateral scenarios and false alarm scenarios. Based on the findings of the first study, the second main study examined the effects of warning direction cues and warning object cues in an urban setting regarding lateral intersection scenarios, frontal scenarios and unnecessary warning scenarios. The findings were discussed individually for each study (see section 3.4 and 4.4). Then I associated the results of both studies to the introduced warning process model (see section 2.1.2) and gave recommendations how to integrate early ADAS warnings regarding collision avoidance (see section 5).

2.7 Methodical Considerations

I decided to conduct my studies in a **driving simulator** because I needed a high level of standardization to compare driver responses regarding different ADAS warnings in critical driving scenarios. For my research work, a fixed-base simulator was sufficient, because kinesthetic feedback should not have produced much more accurate effects for the examined driving scenarios. Furthermore, I focused on the selection of the Field-of-View (FOV), the mockup and the HMI. The individual simulators setup for each study is described in the methods chapter (see section 3 and 4).

For planning and conducting driving simulator studies, **Simulator Sickness** plays an important role. Not every participant is able to drive in a driving simulator without having symptoms of Simulator Sickness. Simulator Sickness symptoms resemble symptoms from seasickness: e.g. visuomotor dysfunctions (eyestrain, blurred vision), mental disorientation (difficulty in concentrating, apathy), nausea, drowsiness and headache (Owen, 1999). Dependent on the simulator and study design, approximately 10% to 60% of participants may suffer from Simulator Sickness. To evaluate symptoms of Simulator Sickness, the Simulator Sickness Questionnaire (Kennedy & Lane, 1993) can be used. One explanation of Simulator Sickness is the Sensory Conflict Theory from Reason & Brand (1975), which describes the mismatch between sensory impressions of different modalities. For example, a fixed-base simulator presents the visual feedback of driving, but does not provide the kinesthetic feedback of driving (motion). This leads to a mismatch between the visual and vestibular perception system of the participant and causes symptoms of Simulator Sickness. Based on my experience with conducting simulator studies and suggestions of other authors, e.g. Owen (1999), there are many factors which can influence the drop-out rate caused by Simulator Sickness: e.g. simulator FOV, complexity of visual flow, pitching movements' feedback, air-conditioning, and detailed participant instructions. For my studies, I optimized driving simulator parameters and gave detailed study instructions to participants who were trained in the simulator to achieve a minimum participant drop-out rate.

3 Main Study 1

3.1 Study 1 Background

To examine warning specificity of early ADAS warnings, I decided to focus on warning direction cues which can help drivers to orient their attention and gaze at possible hazards. Regarding the warning process, warning direction cues can positively influence the first processing steps (attention and perception) of the driver (warning receiver) and thereby may also influence all following warning and hazard processing steps. Furthermore, many lab experiments and some simulator studies (e.g., Fricke, 2009; Cristy Ho & Spence, 2009; Thoma, 2010; see section 2.3.3) showed that a warning direction cue can facilitate responses to an object or specific areas of interest, e.g. hazards. Because these findings suggest that auditory warning direction cues can facilitate driver's responses so that he hardly ignores auditory signals, warning direction cues were implemented in auditory modality for Study 1. These auditory warnings were designed to have an intensity within the auditory comfort range, an appropriate urgency for collisions, and were easy to localize, e.g. through the usage of two frequencies and an atonal structure (see section 2.3.1 and 3.2.4.1).

To analyze and compare the effects of warnings with direction cues, the Master Alert is suited, see section 2.5.2. The Master Alert represents a warning that does not contain specific warning cues for different hazards and thereby can be compared to warnings that contain more specific warning cues. Studies (Cummings et al., 2007; Thoma, 2010) that examined the Master Alert for imminent ADAS warnings did not find clear evidence of driver performance differences between specific warnings and the Master Alert. Regarding these findings, a late warning onset or the settings of the examined scenarios may be the reason for the missing effects of warning specificity. If drivers have to respond in close time distance to hazards after perceiving a warning, specific warning information may not be further processed by them, especially because they have to attend and respond to the hazardous situation.

This thesis focuses on early warnings, which should offer drivers the possibility to process specific warning cues and thereby help them to adapt their behavior to a hazardous situation. For an early warning, drivers do not necessarily have to brake instantly and have about 1 to 1.5 s left to respond to a possible hazard, depending on the perception and evaluation of relevant hazards. However, an earlier detection of hazards may still lead to an earlier braking response. To investigate drivers' responses to early warning direction cues, Study 1 exams whether warning direction cues facilitate the detection of possible hazards and how drivers respond to associated hazards compared to a Master Alert.

If drivers are always able to respond to different hazardous scenarios by frontal attention, a specific warning which contains direction cues may not be more effective than a Master Alert. I implemented a spatial hazard variation of lateral and frontal warning scenarios to Study 1 to address this point. The lateral warning scenarios were designed to get drivers to focus their attention and look left or right and thereby offering them the possibility to spot laterally approaching hazards (cross traffic). On the contrary, for the implemented frontal warning scenarios, drivers should be able to respond to a hazard by frontal attention, e.g. watching through the windshield. Furthermore, the findings of Cummings et al. (2007) suggest that a Master Alert is perceived as appropriate warning for differing driver responses. To confirm this, two types of frontal warning scenarios were implemented in Study 1: Scenarios in which participants have to steer and scenarios in which participants have to brake. All scenarios were placed into a test track with rural environment and a speed limit of 80 kph.

In addition to that, Study 1 includes false alarm scenarios to examine how warning direction cues influence the driver's response if no hazardous object is present. A recent study of Herzberg (2012) indicated that warning specificity can affect warning acceptance ratings and driver performance regarding false alarm scenarios. Concerning false alarms, it may also be possible that driver responses to specific warning elements can be learned and lead to unintended driver behavior in false alarm scenarios, e.g. braking and especially visually searching for possible hazards.

To analyze the driver behavior regarding the warning direction cues, I conducted Study 1 in a fixed base driving simulator with 300° FOV and eye tracking (see section 3.2.2). This big FOV angle allowed me to place hazards at pronounced lateral positions, e.g. left or right at intersections. Additionally, a fixation task with scene occlusion was implemented to standardize the warning onset and the participant's gaze position before warning scenarios. This represents a unique standardization approach with the possibility to examine the glance behavior of drivers more detailed compared to present Master Alert studies (e.g., Cummings et al., 2007; Thoma, 2010; see section 2.7).

Study 1 measured the glance behavior (time of hazardous object fixation and associated horizontal head movements), the accelerator pedal reaction times, the brake pedal reactions times (see section 2.2.3) and the number of collisions, to analyze participant's attention and responses regarding the implemented warnings and hazards. Furthermore, for frontal warning scenarios which highlight a steering response, the time to return to the center of the lane was assessed. To evaluate the warning system acceptance and the quality of implemented scenarios, questionnaires and interviews were used.

Study 1 Hypotheses

In general participants should benefit from a warning with direction cue for their hazard response. Compared to the Master Alert, the benefit by the "warning with direction" will lead to a faster hazardous object fixation and more head rotation. Furthermore, the factor "Warning scheme" (Master Alert, warning with direction) may lead to differences in the driving behavior regarding the accelerator pedal reaction times and brake reaction times. Effects of "Warning scheme" will be present for lateral scenarios, but may also occur with frontal scenarios and false alarm scenarios. For false alarms, the warning with direction may lead to more horizontal head rotation compared to the Master Alert, indicating more visual search behavior.

3.2 Study 1 Method

3.2.1 Participant Sample

Twenty-seven normal hearing drivers participated in this experiment. One participant was excluded from the data analysis (age of 78) because of consistently missing braking reactions, two participants were excluded because of multiple interruptions of the experiment. The resulting sample consisted of 24 participants (10 male) from different professional and educational levels (age of *M* = 35.7, *SD* = 14.2, 20 to 67 years). All participants were recruited, trained for simulator studies and paid by the WIVW GmbH. Before the participants started driving in the simulator, their health condition was assessed. Only participants in good health condition were allowed to drive in the simulator. Participants were able to take a break or to abort the study.

3.2.2 Apparatus

3.2.2.1 Simulator

The experiment was conducted on a fixed-base driving simulator (WIVW GmbH) with 300° field of view, see Figure 3.1. The 300° projection was realized by five DLP projectors, each with a resolution of 1400x1050 pixels. Three LCD displays were used as rearview mirror and side mirrors. The mockup was based on a Sprinter-class vehicle with automatic transition. Participants interfaced with the brake pedal, accelerator pedal and steering wheel. The speedometer, turning signals, seat adjustments were fully functional. Auditory output, namely vehicular motor sounds and the pertinent alarm warnings were broadcasted through a connected headphone (Sony, 10 – 24000 Hz, sensitivity of 102 dB/mW). Nine PCs (Intel Core 2 Duo, 3 GHz, 4 GB RAM, NVidia

GeForce GTS 250) and the SILAB software (WIVW GmbH) were used for simulation purposes. The PCs were connected by Gigabit-Ethernet. SILAB recorded data (e.g., vehicle dynamics, trigger signals) with a frequency of 60 Hz. For fixation task (see section 3.2.3) a 10” LCD display was used that was mounted on the middle console. Furthermore, participants could communicate with the experimenter by microphones and speakers.

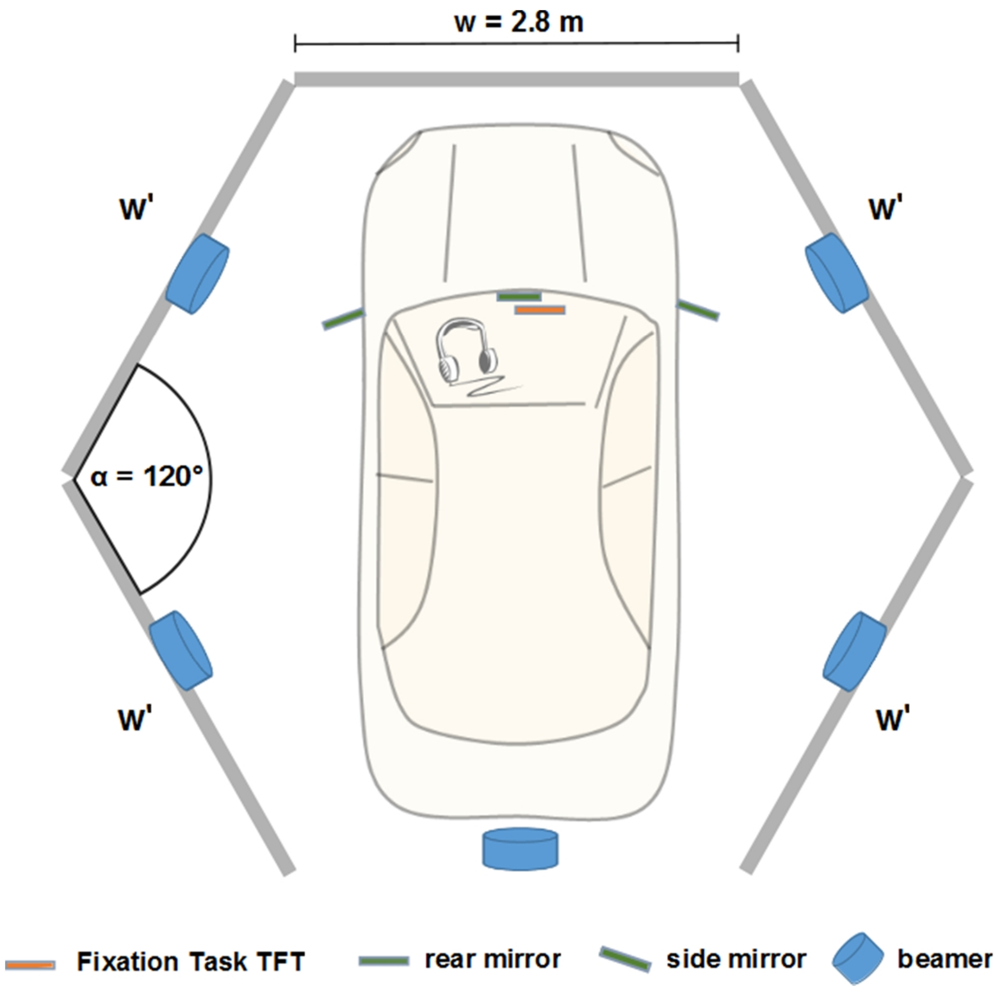


Figure 3.1: Simulator setup of Study 1 showing positions of the mockup, the beamers, the rear mirror, the side mirrors and the fixation task TFT.

3.2.2.2 Eye-tracker

A four-camera eye-tracker from Smart Eye AB mounted in the mockup was used for eye-tracking. Due to an individual calibration for each participant, it could measure eye movements and fixations for angles up to +/-60° from middle of front view, including the necessary head rotation. The eye tracking data were recorded with a frequency of 25 Hz.

3.2.2.3 Questionnaires

Before participants started the driving task, they filled in a questionnaire assessing driving experience and health condition. After completing the test track, participants filled in a questionnaire which mainly focused on the evaluation of scenarios and implemented warnings. Following subjective variables were analyzed:

- Difficulty of the driving task (5-point scale, from “very easy” to “very difficult”)
- Usefulness of the used warnings (5-point scale, from “not useful” to “very useful”)
- Criticality of the warning scenarios (4-point scale, from “not critical” to “very critical”)
- Satisfaction with the quality of driving in a test track (4-point scale, from “very unsatisfied” to “very satisfied”)
- Open questions and interview: Evaluation of the warning system, response to warning, predictability of warning scenarios, perception of warning direction cues

3.2.3 Fixation Task and Occlusion

To standardize the initial gaze position in warning situations, an occlusion and fixation task was used. During driving the test track, the simulation projection was occluded overall 86 times for 1.8 to 2.1 s, meaning the whole projection scene was cleared black. During the occlusion the simulation continued. The occlusion time was adapted from usual distraction times in driving context (see section 2.3.3). To reduce possible learning effects that cover the duration of occlusions, the interval duration was pre-randomized. During the occlusions, participants should fixate a white fixation cross with black background that was displayed on a 10” TFT display mounted on the center stack (fixation task).

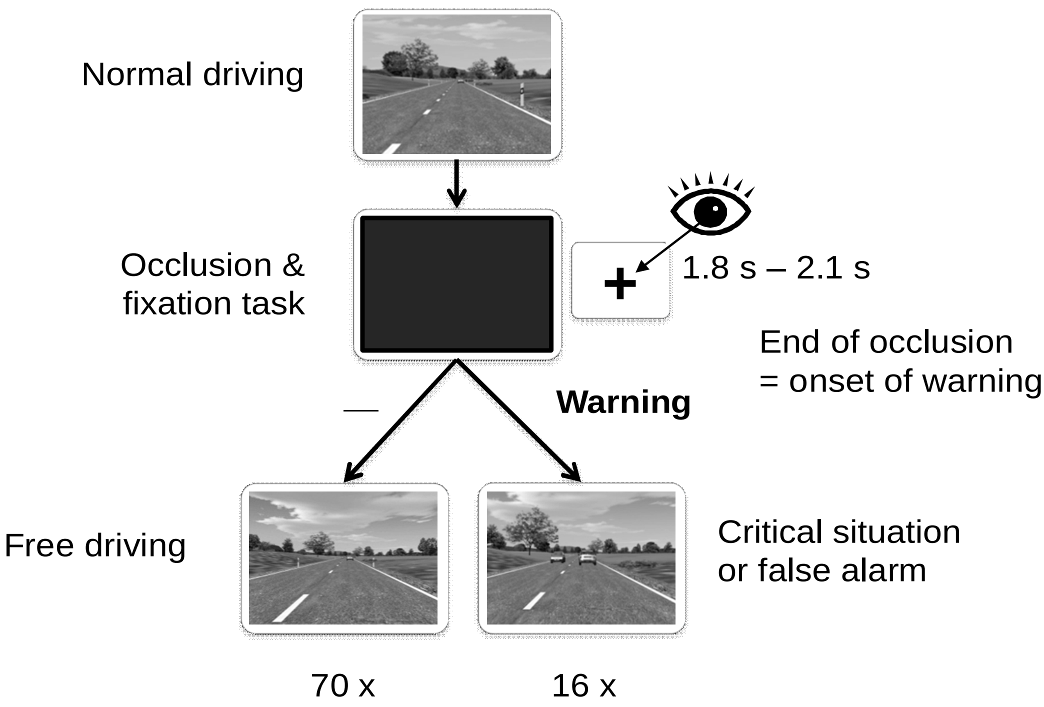


Figure 3.2: Procedure for occlusion and fixation task. After normal driving in the test track, an occlusion appeared at 86 positions. Meanwhile the occlusions participants had to fixate a fixation cross at a TFT which was placed at the center stack of the mockup. In 16 scenarios a warning was emitted after the occlusions. In all other situations the scenario continued normally after the occlusions.

The fixation task was used to standardize the starting point of participant gaze for warning scenarios. In 70 neutral scenarios with disappearing occlusion no warning was emitted and the scenarios continued normally, see Figure 3.2. A warning was emitted in 12 critical scenarios and 4 false alarm scenarios with disappearing occlusion, for example: Often participants had to follow a leading vehicle and after occlusions nothing unusual happened. Instead in a critical scenario at the end of the occlusion a warning was emitted and the leading vehicle suddenly braked abruptly (scenario: frontal collision alert). Because participants fixated the fixation cross at the beginning of the warning, the eye movements could be better compared for different warning scenarios.

3.2.4 Experimental Design

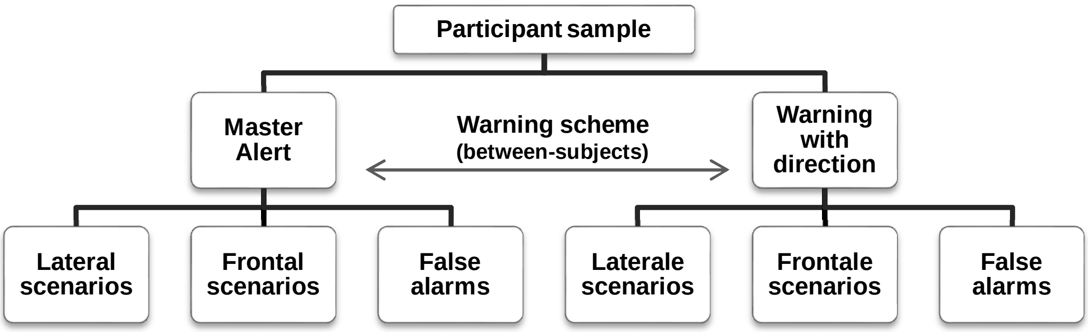


Figure 3.3: Experimental design of Study 1. Two groups were assigned randomly. Each group had the same set of lateral, frontal and false alarm scenarios, but the warning scheme differed.

The factor “Warning scheme” was applied as between-subjects factor with two levels (Master Alert, warning with direction). Participants were randomly assigned to two groups according to the two levels of “Warning scheme”, see Figure 3.3. Both groups had to drive the same test track consisting of lateral scenarios, frontal scenarios, false alarm scenarios and many neutral intersections as well as connecting roads. The individual “scenarios” of each scenario group were used as a within-subjects factor.

3.2.4.1 Warning Scheme

As Master Alert (Warning scheme level 1) two overlaid sine tones with a frequency of 2000 Hz and 2500 Hz, a sound level of 75 dB, and 5 cycles of 100ms on/off-phases were used. For the Master Alert the warning tones were only broadcasted from frontal direction. For the warning with direction (Warning scheme level 2) the same tones as for Master Alert were emitted from the hazard direction: Left, right and frontal. The onset of the auditory warning was set simultaneously with the disappearing of the implemented occlusions with a TTA of 3.9 s in lateral scenarios and TTC of 2.5 s in frontal scenarios. The warning onset for the lateral scenarios was intended to be in range of 2 s before the last possible warning onset (T0). However, to match the scenarios timing and to increase their realism, it was implemented with 3.9 s TTA, which is below the theoretical value of 4.3 s TTA regarding T0 + 2 s (see section 2.2.3).

In a pretest with 5 participants, we confirmed that participants can discriminate the locations of the tones. Participants had to drive 80 kph on a straight rural road and listen to pre-randomized and permuted order of warnings coming from frontal, left and right. With the 5.1 Dolby Surround setup we found following mean classification of warning directions by the participants: front *M* = 86% (*SD* = 19%), left *M* = 89% (*SD* = 12%), right *M* = 86% (*SD* = 17%). To improve warning direction classifications, we used a headphone instead of the 5.1 Dolby Surround System. The results were following classifications of warning directions by five additional participants: front *M* = 91% (*SD* = 15%), left *M* = 97% (*SD* = 6%), right *M* = 97% (*SD* = 6%).

3.2.4.2 Warning Scenarios

The warning scenarios were equal for each participant and grouped into three categories: Lateral scenarios, frontal scenarios and false alarms. The order of warning scenarios was pseudo randomized once for the test track. For the study the order was the same for all participants. Table 3.1 shows the numbers of used scenarios.

Table 3.1: Warning scenario groups and scenario count.

Scenario group	N
Frontal scenarios	6
Lateral scenarios	6
False alarms	4

3.2.4.2.1 Lateral Scenarios

For lateral scenarios the hazard (bike, car and motorbike) appeared left or right at T-intersections with an angle of 54° to the middle of the frontal view, seen from the driver's perspective. For all intersections the ego-vehicle had the right of way. In 2 scenarios the hazardous objects (bike and wild boar) were approaching the ego-vehicle at the intersection from a nearby meadow instead from the street. The speed of the hazardous objects (car, bike, motorbike) was set to 9 m/s for lateral intersection scenarios and 3.5 m/s for lateral scenarios with hazard approaching from meadow. In all lateral scenarios the warning onset was 3.9 s time to arrival (TTA) to the hazardous object. To spot the hazardous object as early as possible, participants had to move their head right or left, see Figure 3.4. A fast hazardous object fixation was not possible without head movement.

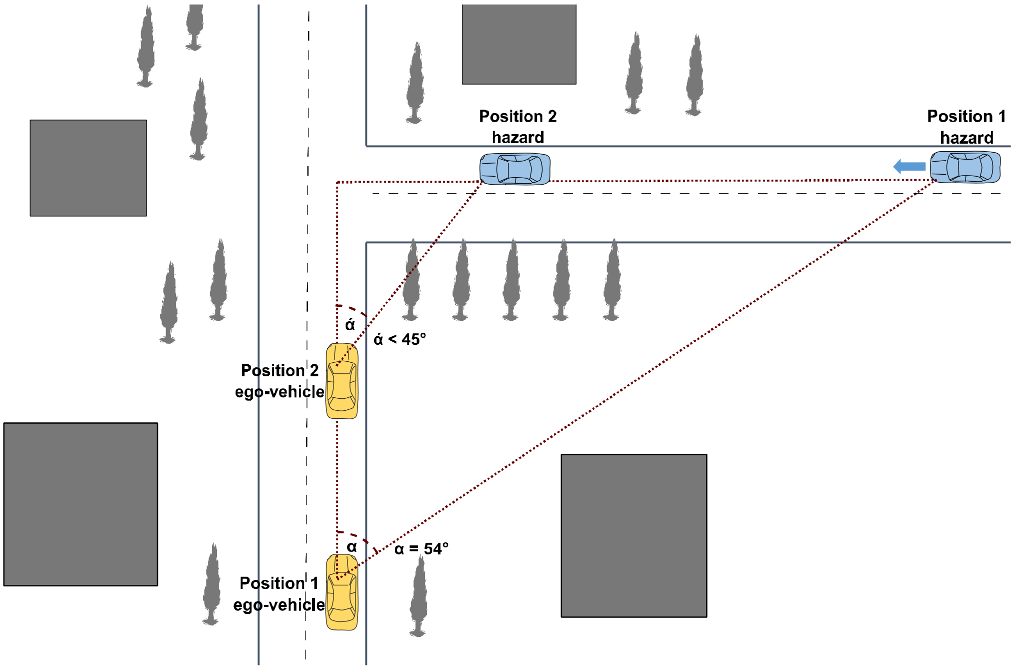


Figure 3.4: This figure shows an example of a lateral warning scenario with a vehicle approaching from the right side. At position 1, the warning was broadcast with an angle of α = 54° between the frontal view of the ego-vehicle and the hazardous vehicle. When the vehicles approached the intersection this angle became smaller, see position 2.

There were 6 critical, lateral intersection scenarios:

1) Motorbike approaching the intersection from the right side (MBIKE_R)
2) Car approaching the intersection from the right side (CAR_R)
3) Bike approaching the intersection form the right side starting from a meadow nearby the intersection (BIKE_R)
4) Motorbike approaching the intersection from the left side (MBIKE_L)
5) Bike approaching the intersection from the left side (BIKE_L)
6) Wild boar approaching the intersection form the left side starting from a meadow nearby the intersection (WB_L)

3.2.4.2.2 Frontal Scenarios

For frontal scenarios participants could spot the hazard and respond to the warning situation just by looking to the frontal view (frontal attention) without moving their heads.

Overall there were 6 critical, frontal scenarios. For half of frontal scenarios the driver's response differed: In 3 scenarios (1 to 3) the participant's car was laterally moved while occlusion and participants had to steer back to the center of the road. In the other 3 frontal scenarios (4 to 6) the participants had to brake in order to avoid a collision:

1) Leaving lane on the wrong side of the road and oncoming traffic (OT)
2) Leaving lane on the wrong side of the road (OTb)
3) Road departure to the right (RD)
4) Abruptly braking leading vehicle (FC)
5) Abruptly braking leading vehicle 2 (FCb)
6) Wild boar crossing road from frontal right (WB)

For frontal scenarios (4 to 6) the warning was emitted with time distance of 2.5 s TTC to the hazardous object.

3.2.4.2.3 False Alarms

To investigate how drivers responded to false alarms (FA), 4 scenarios with warnings and no critical hazardous object were implemented. Two false alarms were emitted at straight, rural road sections, two at intersections. In false alarm scenarios there was no hazardous object that could be spotted by the participants. The warning with direction (Warning scheme level 2, see section 3.2.4.1) was broadcast from left and from right for the two false alarms at straight rural road sections.

3.2.5 Test Track

3.2.5.1 Course Generation Helper Tool

To implement a homogeneous test track with many neutral driving situations and similar looking critical scenarios, a helper-tool (CGHT) was developed in C++. It was used to generate a pseudo randomized course with random variation of height profile, curve profile, traffic and surrounding objects (trees, bushes, etc.) and also random insertion of intersections and occlusions, see section 1.11.3. The CGHT produced SILAB configuration files that could directly be used by SILAB simulation software (WIVW GmbH). The main purpose of CGHT was to develop a uniform course with variations through the entire route, thereby reducing the predictability of warning scenarios.

3.2.5.2 Track composition

On average participants drove about 1.5 h to complete the test track. The overall track length was 90 km. As road type, two lane rural roads were used. The track consisted of straight parts, curves, rural and suburban T-intersections. The driving environment was filled with surrounding trees, wood, vineyards, mountains and meadows. To standardize speed and timings for the used scenarios, maximum speed was locked to 80 kph. The participants had to constantly hold the accelerator pedal with middle force to maintain the speed of 80 kph. To avoid effects of tiredness, participants had to regulate their speed in curves and parts with leading vehicles. Random traffic was simulated all over the track, including leading vehicles, oncoming traffic, approaching vehicles from behind and overtaking vehicles. Traffic in neutral scenarios was comparable to traffic in critical scenarios, except the emerging critical objects. The track started with 6 occlusions inserted as training trials. All other occlusions were inserted by the CGHT (see 3.2.5.1) at random positions on straight road parts and intersections.

3.2.6 Experimental Procedure

Overall the experiment took about 2.5 h per participant including individual eye tracking calibration, questionnaires and driving the test track. At first, the participants were informed about the experiment procedure and had to write a privacy statement that covers the usage of data from eye-tracking, driving dynamics, interviews and questionnaires. Then a video of participants head rotation and fixation of each of the 4 eye-tracking cameras was recorded. This video was used to create individual eye-tracking profiles and increase eye tracking performance. The calibration procedure took about 20-25 min.

The participants were informed that they will drive a rural test track, have to maintain 80 kph (if possible) and stay on the right lane. Participants were told to only brake or overtake if it is necessary. They were informed about the maximum speed lock at 80 kph. Participants were also instructed to fixate the fixation cross at the center stack display of the mockup and hold their speed during occlusions. Participants were not further informed about the warning system which was used for warning scenarios.

After participants were randomly assigned to 2 groups (Master Alert, warning with direction), they drove through 6 neutral training scenarios to practice the fixation task. Already after 2 training trials, most participants were able to accomplish the fixation task perfectly. The training scenarios were part of the main test track with many neutral T-intersections and straight or curved connecting parts.

Both groups of participants drove the same test track, only the warning scheme was different for each group. Over the whole track, participants had to respond to 80 randomly placed occlusions with fixation tasks, including 16 with warnings. At half of the test track, participants were asked to take a break. After completing the test track, the participants filled in a questionnaire and were interviewed about the test track, the used warnings and the experimental setting.

3.2.7 Dependent Variables

The following dependent variables from eye-tracking data were analyzed:

- Time of hazardous object fixation (ms)

  Criteria: Time from warning onset until participants fixated the hazardous object in critical scenarios. The first fixation of hazardous object with subsequently tracking, e.g. following the object or saccade back to road and back to object, was used. The fixation time was determined by manual inspection of eye-tracking video data combined with vehicle data.

- Maximum, horizontal head rotation in hazard direction (degree)

  Criteria: Maximum angle of head rotation into hazard direction in the first 2 seconds after warning onset. Absolute values were used for comparison. Maximum head rotation indicates whether the participants moved their heads early to the hazardous object because this object approached the crossing and thus moved centrally.

- Maximum, horizontal head rotation for false alarms (degree)

  Criteria: Maximum angle of head rotation in the first 2 seconds after warning onset. Absolute values were used for comparison. The maximum head rotation for false alarms indicates whether the participants moved their heads to the left or the right side after a false alarm.

The following dependent variables from vehicle data were analyzed:

- Time to return to the center of the lane (ms)

  Criteria: Time from warning onset until the participants returned to the center of the lane. This applies only to critical, frontal scenarios in which the participant's car was laterally moved during the occlusion and when the participants had to steer back to the center of the lane.

- Accelerator pedal reaction times (ms)

  Criteria: Time from warning onset until the accelerator pedal was released completely.

- Brake reactions times (BRT, ms)

  Criteria[5]: Time from warning onset until 2% of the mean, maximum braking pressure of all participants was reached. All brake responses where addressed by these criteria.

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[5]I chose 2% as criteria to ensure that all brake reaction are over the recording noise level.

- Number of collisions with hazardous objects

  Criteria: All collisions with hazardous object, including slight and serious collisions.

- Number of braking reactions for false alarms

  Criteria[6]: Absolute and relative number of brake reactions for false alarm scenarios. The relative numbers are shown in percent. Only brake reactions that reached 2% of the mean, maximum braking pressure of all participants were included.

The following subjective scales were analyzed (description see 3.2.2.3): Difficulty of the driving task, usefulness of the used warnings, criticality of the warning scenarios, satisfaction with the quality of driving in test track and participant comments from open questions and interviews.

3.2.8 Data Preparation

Dependent variables from vehicle data and eye-tracking were pre-processed with Matlab and used for further analysis. To ensure the correctness of parameterized eye-tracking variables, all eye-tracking data from warning scenarios were manually inspected and corrected. For further data processing and analysis the software Matlab, SPSS and Excel were used.

[6] I chose 2% as criteria to ensure that all brake reaction are over the recording noise level.

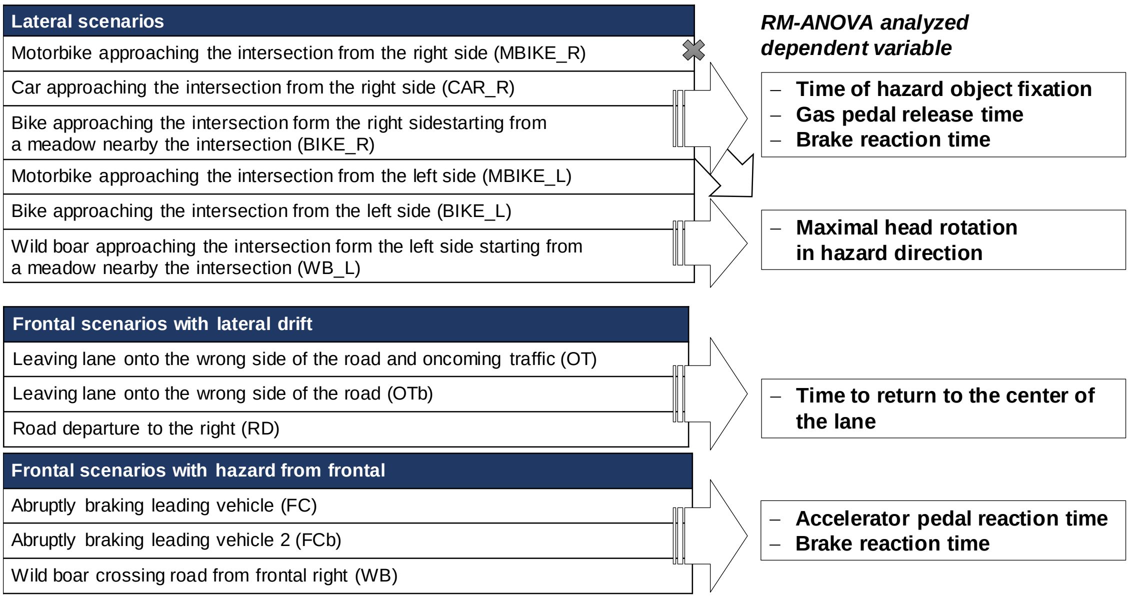


Figure 3.5: Overview of critical scenarios and analyzed dependent variables. Depending on the type of scenario, a specific set of dependent variables was analyzed in RM-ANOVAs.

Frontal, lateral and false alarm scenarios were analyzed separately. For each dependent variable of vehicle data and eye-tracking data, a Repeated Measurement ANOVA (RM-ANOVA) with the between-subjects factor "Warning scheme" (Master Alert VS warning with direction) and the within-subjects factor "scenarios", e.g. all individual lateral scenarios, was conducted.

For lateral scenarios the time of hazardous object fixation, maximum head rotation in hazard direction, accelerator pedal reaction time and brake reaction time were analyzed in a RM-ANOVA. For frontal scenarios with lateral drift (OT, OTb, RD) the time to return to the center of the lane was analyzed in a RM-ANOVA. In these frontal scenarios participants had to steer back to the center of the lane after the occlusion. For all other frontal scenarios the accelerator pedal reaction time and brake reaction time were analyzed with a RM-ANOVA.

For lateral and frontal scenarios, the number of collisions was only analyzed descriptively because they occurred rarely. Furthermore, the number of brake reactions in false alarm scenarios was only examined descriptively because they also occurred rarely and showed very little differences regarding the warning schemes.

For frontal scenarios the head rotation was not analyzed because in both experimental groups (Warning scheme) participants' head rotations stayed under 10°. Also the time of the hazardous object fixation was excluded for frontal scenarios. In frontal scenarios participants usually directly fixated the hazardous object after the occlusion (e.g., frontal collision scenario). One of the critical scenarios, motorbike from right, was excluded from further analysis. Motorbike from right was the first lateral scenario. It seems that this scenario was too difficult because all participants required longer to respond to this hazard than to the other hazards, if they responded at all. Regarding the excluded scenarios where a motorbike came from the right side, the number of collisions was three to four times higher than for other lateral scenarios. In two lateral scenarios, a wild boar or bike coming from lateral meadow, the scenarios setting and starting speed of hazardous object caused much variance in participants' reactions. For these two scenarios only maximum head rotation in hazard direction was analyzed. It seems that hazardous objects coming from a meadow were evaluated differently than hazardous objects coming from the road. To compare the brake reaction times and the head rotation in false alarm scenarios, *t*-tests for independent samples were used.

The significance level for statistical calculations was set to $\alpha = .05$. The RM-ANOVA requirement of normal distribution was tested with Kolmogorov-Smirnov-Tests. The RM-ANOVA requirement of equable error variances was checked with a Levene´s-Test and a significance level of $\alpha > .20$. In cases a Mauchly's test for sphericity indicated that the sphericity assumption was not set, a Huynh-Feldt correction of degrees of freedom was applied. Interaction effects were examined with *t*-tests for independent samples and dependent samples.

3.3 Study 1 Results

The subsequent section describes the results of behavioral variables of eye-tracking and vehicle data. These results are grouped by scenario types: Lateral scenarios, frontal scenarios and false alarms. In the next step, section 3.3.2 shows the results of questionnaires and open questions.

3.3.1 Behavioral Data

3.3.1.1 Lateral Scenarios

Main effects of "Warning scheme" were found for lateral intersection scenarios[7], see Table 3.2. Participants of the group "warning with direction" showed faster hazard fixation and significantly more intensive head rotation (see Figure 3.6) than participants of the group "Master Alert". Accelerator pedal reaction time and brake reaction times did not differ for "Warning scheme". The factor Scenarios[8] showed a main effect on time of hazardous object fixation, accelerator pedal reaction time and brake reaction time.

Table 3.2: Main effects and interaction effects of "Warning scheme" and Scenarios on each analyzed dependent variable (lateral scenarios)

Dependent variable	Warning scheme (between-subjects)	Scenarios (within-subjects)	Scenarios x Warning scheme
Time of hazardous object fixation	$F(1,22) = 7.63$, $\boldsymbol{p < .05}$*, $\eta_p^2 = .31$	$F(2,44) = 30.85$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .63$	$F(2,44) = .14$, $p=.87$, $\eta_p^2 = .01$
Maximum horizontal head rotation[1]	$F(1,22) = 8.77$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .35$	$F(4,88) = 2.31$, $p = .06$, $\eta_p^2 = .10$	$F(4,88) = .63$, $p = .64$, $\eta_p^2 = .02$
Accelerator pedal reaction time	$F(1,22) = 1.15$, $p = .30$, $\eta_p^2 = .08$	$F(2,44) = 4.75$, $\boldsymbol{p < .05}$**, $\eta_p^2 = .18$	$F(2,44) = 1.34$, $p = .27$, $\eta_p^2 = .06$
Brake reaction time	$F(1,21) = 7.42$, $p = .40$, $\eta_p^2 = .03$	$F(2,42) = 8.81$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .30$	$F(2,42) = 1.42$, $p = .25$, $\eta_p^2 = .06$

[1] including two lateral intersection scenarios with objects approaching from meadow

The results of the maximum head rotation are shown first and subsequently boxplots for each of the other dependent variables. The reason therefore is the high significant effect of "Warning scheme" on the maximum horizontal head rotation.

[7]For description of scenarios and variables for the RM-ANOVAS see section 3.2.8.

[8]Effects of the factor Scenarios were mainly determined by the differing hazardous objects. Thus, only main effects of scenarios are reported.

Figure 3.6 shows the maximum head rotation into the direction of the hazard for lateral scenarios. Warning with direction led to a greater head rotation angle into hazard direction than the Master Alert. For car from right side and motorbike from left side the *t*-tests showed no difference between warning with direction and Master Alert. For all other lateral scenarios the *t*-tests for "Warning scheme" were significant or marginally significant, see Figure 3.6.

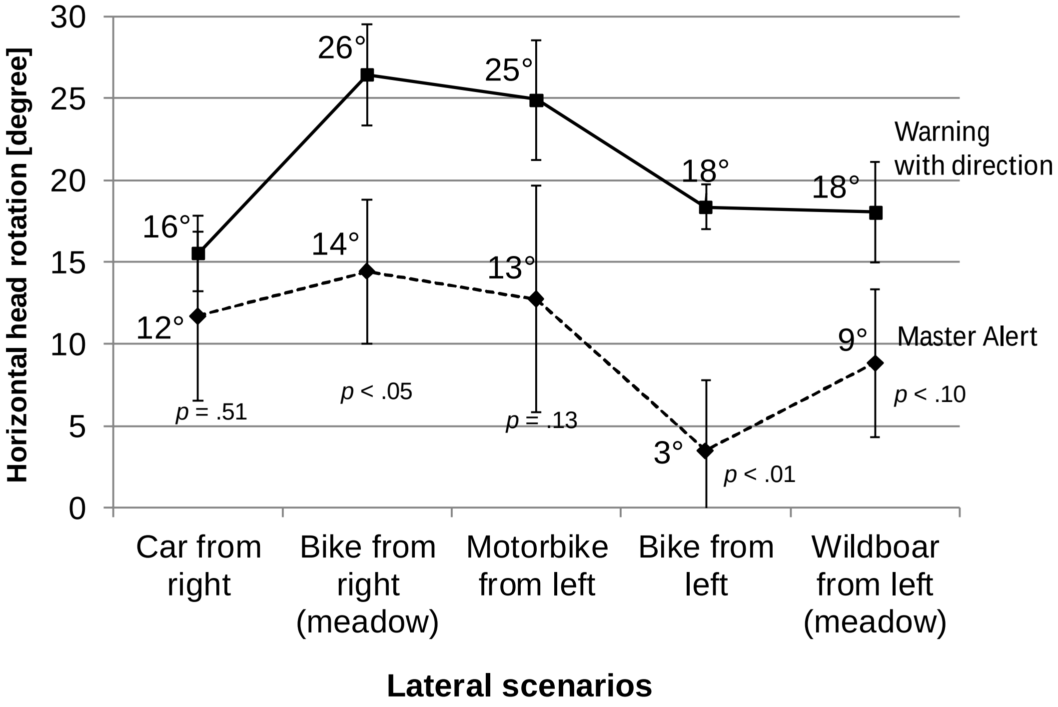


Figure 3.6: Maximum horizontal head rotation (absolute) in the direction of the hazard after warning onset for lateral scenarios. Alpha levels of mean comparisons between the warning schemes "warning with direction" and Master Alert are illustrated for each scenario.

Figure 3.7[9] shows boxplots for the time of the hazardous object fixation, accelerator pedal reaction time and brake reaction time for each lateral scenarios of Study 1. Scenario motorbike from right is included to illustrate the large variance, see Figure 3.7 and section 3.2.8. In general, the hazard type and the scenario setting, e.g. hazard approaching from meadow compared to hazard approaching from road, led to differences in all measured dependent variables. In addition to that, "Warning scheme"

[9]No addition boxplots were used because the maximum head rotation in hazard direction for lateral scenarios is already illustrated in Figure 6.

led to a faster time of hazardous object fixation for lateral scenarios with hazards coming from left or right road at the intersection.

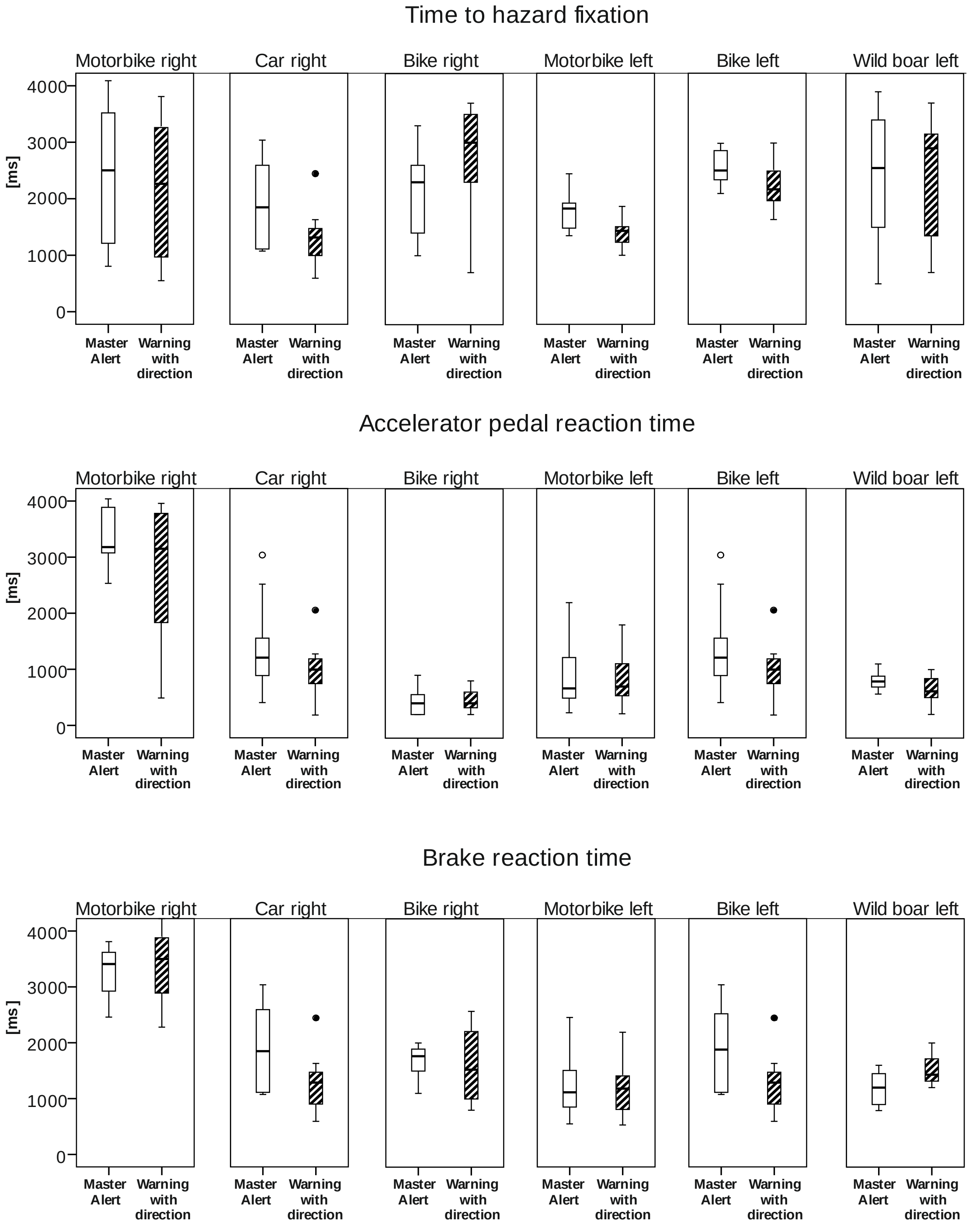


Figure 3.7: Boxplots showing time of hazardous object fixation, accelerator pedal reaction time and brake reaction time for each lateral scenario.

Figure 3.8 shows descriptively that the warning with direction led to a faster hazardous object fixation, faster accelerator pedal reaction time and faster brake reaction. As Table 3.2 shows only the time of hazardous object fixation and the maximum horizontal head rotation in hazard direction were significant for “Warning scheme”. For accelerator pedal reaction time and brake reaction time, a considerable amount of variance led to an insignificant comparison between Master Alert and warning with direction, see Table 3.2 and boxplots at Figure 3.7.

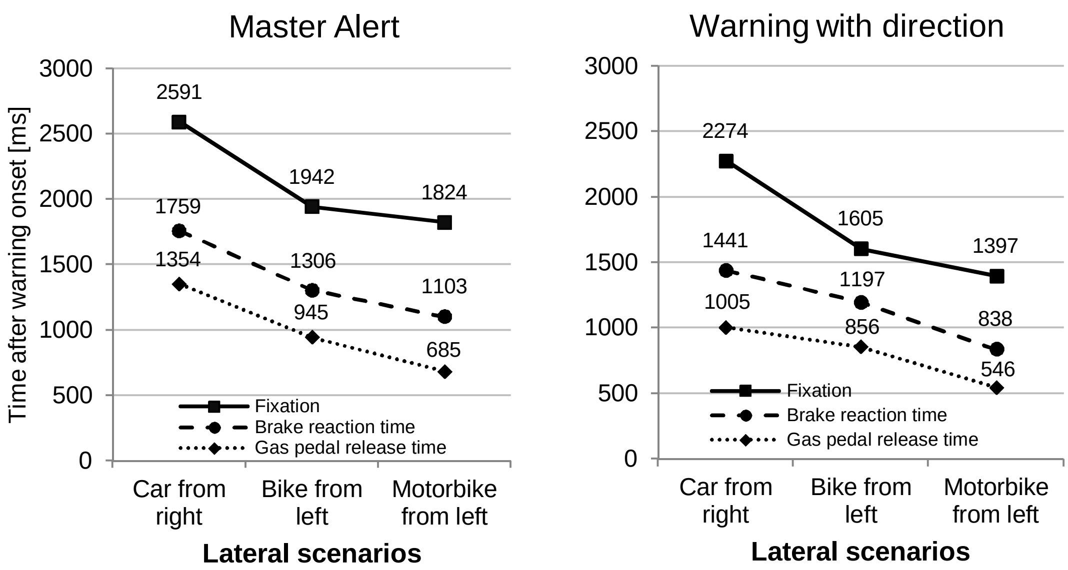


Figure 3.8: This figure illustrates the means of time of hazardous object fixation, accelerator pedal reaction times and brake reaction times after warning onset for three lateral scenarios in “Master Alert” and “warning with direction” condition. These three scenarios were selected because the corresponding hazards were always approaching from the right or the left road at examined intersections. Lateral scenarios with hazards approaching from meadow were excluded.

The number of collisions did not differ for the warning schemes, see Table 3.3. Because collisions occurred only rarely, no comparison tests for the Warning scheme were conducted. In the first lateral scenario “motorbike from right” (MBIKE_R) considerable more collisions occurred than for all other lateral scenarios.

Table 3.3: Number of overall collisions for lateral scenarios[10] grouped by “Warning scheme”

Warning scheme	Number of collisions					
	MBIKE_R	CAR_R	WB_L	BIKE_L	MBIKE_R	BIKE_R
Warning with direction	5	1	2	1	1	0
Master Alert	3	1	0	1	1	0

3.3.1.2 Frontal Scenarios

For frontal scenarios no effects for factor “Warning scheme” were found, see Figure 3.4. The factor scenarios showed a main effect on time to return to the center of the lane and

[10]For list of scenarios see 3.2.4.2.1.

accelerator pedal reaction time. The interaction between “Warning scheme” x Scenarios was significant for the brake reaction time.

Table 3.4: Main effects and interaction effects of “Warning scheme” and Scenarios on each analyzed dependent variable (frontal scenarios)

Dependent variable	Warning scheme (between-subjects)	Scenarios (within-subjects)	Scenarios x Warning scheme
Time to return to center of lane[1]	$F(1,22) = 2.51$, $p = .13$, $\eta_p^2 = .10$	$F(2,44) = 4.23$, $\boldsymbol{p < .05^{*}}$, $\eta_p^2 = .16$	$F(2,44) = .45$, $p = .64$, $\eta_p^2 = .02$
Accelerator pedal reaction time[2]	$F(1,22) = 1.26$, $p = .27$, $\eta_p^2 = .08$	$F(2,44) = 6.00$, $\boldsymbol{p < .01^{**}}$, $\eta_p^2 = .18$	$F(2,44) = 2.87$, $p = .07$, $\eta_p^2 = .06$
Brake reaction time[2]	$F(1,22) = 1.62$, $p = .22$, $\eta_p^2 = .06$	$F(2,44) = 24.36$, $\boldsymbol{p < .001^{**}}$, $\eta_p^2 = .52$	$F(2,44) = 6.54$, $\boldsymbol{p < .01^{**}}$, $\eta_p^2 = .23$

[1] Frontal scenarios with lateral drift: OT, OTb, RD
[2] Frontal scenarios with hazard from frontal: FC, FCb, FLC

The time to return to the lane, the accelerator pedal reaction time and the brake reaction time did not differ for “Warning scheme” in frontal scenarios, see Figure 3.9 and Figure 3.10. To investigate the interaction between Scenarios x “Warning scheme” for the brake reaction time, *t*-tests for independent samples were conducted. Only for scenario abruptly braking leading vehicle (FC) the brake reaction times showed a significant difference for “Warning scheme” $t(22) = -2.79$, $p < .05$. On average, the participants of the group Master Alert responded 289 ms faster than participants of the group “warning with direction” for the FC scenario.

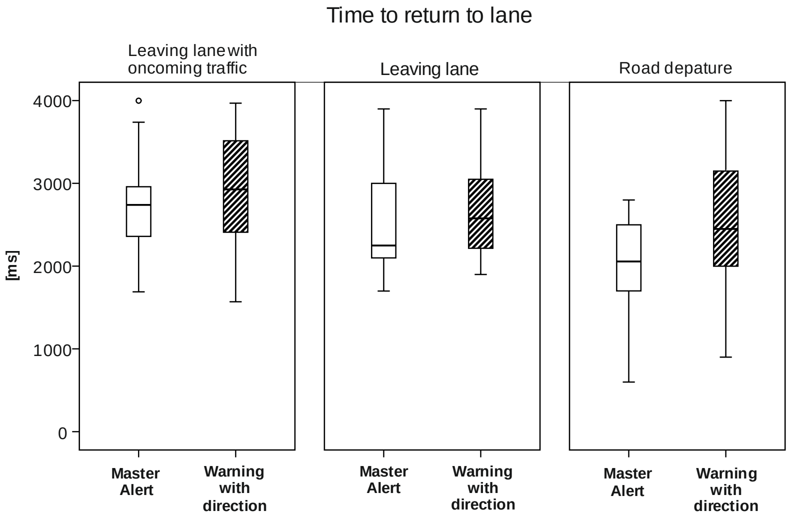


Figure 3.9: Boxplots showing the time to return to center of lane for frontal warning scenarios with lateral drift. During the occlusion, the participant's car was moved laterally. After the occlusion and with the beginning of the warning, participants had to steer back to the center of lane.

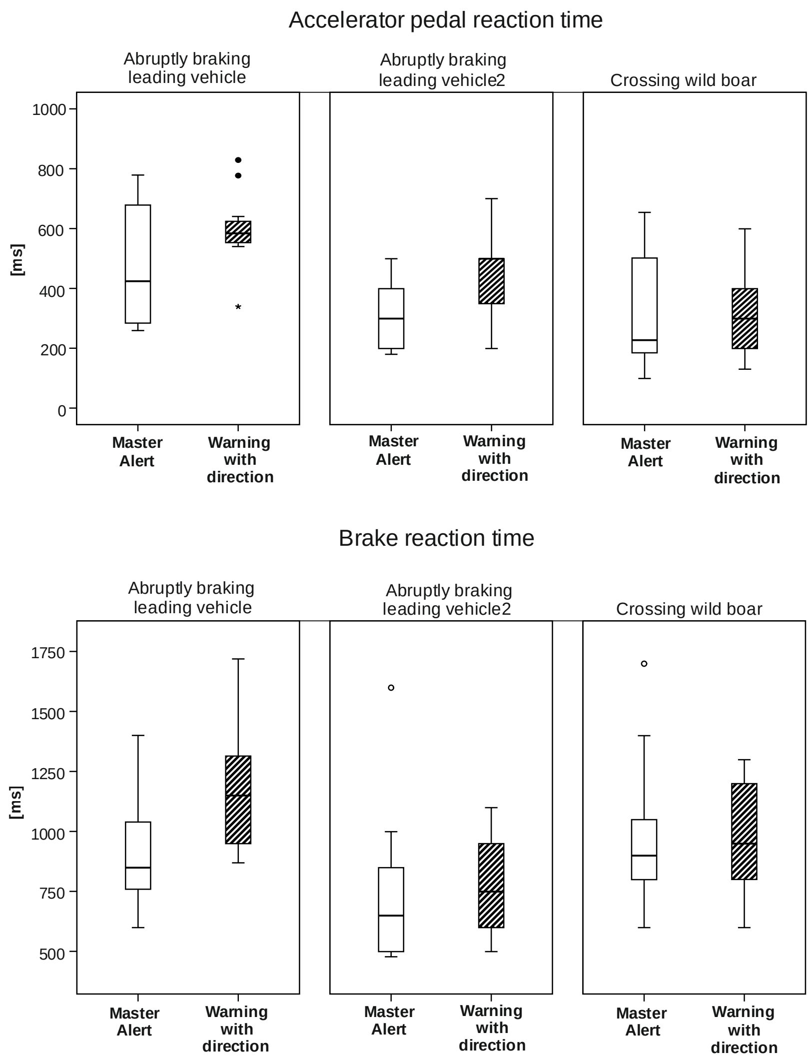


Figure 3.10: Boxplots showing the accelerator pedal reaction times and the brake reaction times for frontal warning scenarios with frontal hazards. After the occlusion and with beginning of the warning participants had to respond to a hazardous object in front of their car.

The number of collisions did not differ for "Warning scheme", see Table 3.5. Because collisions occurred rarely, they were only described.

Table 3.5: Number of overall collisions for frontal scenarios[11] grouped by Warning scheme.

Warning scheme	Number of collisions					
	FC	FCb	LFC	OT	OTb	RDW
Warning with direction	2	1	2	2	0	0
Master Alert	2	1	1	1	0	0

3.3.1.3 False Alarms

For false alarm scenarios the number of brake reactions and horizontal head movement were analyzed. Overall participants showed braking reactions on false alarms in 23% of intersections and 15% of straight rural road sections. Table 3.6 shows the number of brake reactions for false alarm scenarios grouped by "Warning scheme". Because brake reactions occurred only rarely for false alarm scenarios, no comparison tests were conducted.

Table 3.6: Number of brake reactions for false alarm scenarios grouped by "Warning scheme"

Warning scheme	Number of brake reactions for false alarms	
	At intersections	At straight rural road sections
Warning with direction	5	3
Master Alert	6	4

[11]For list of frontal scenarios see 3.2.4.2.1.

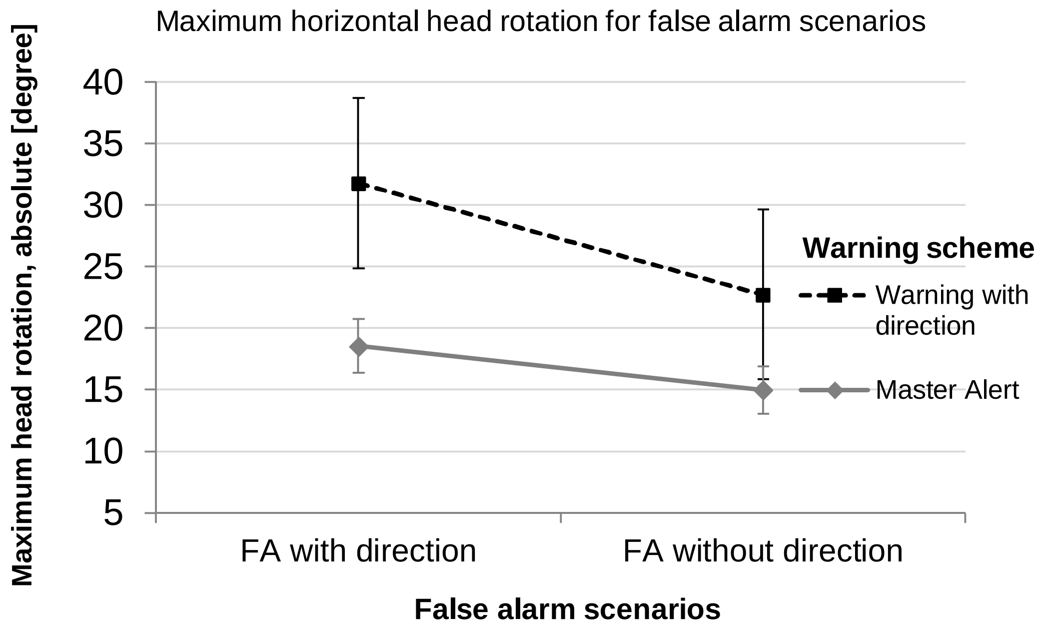
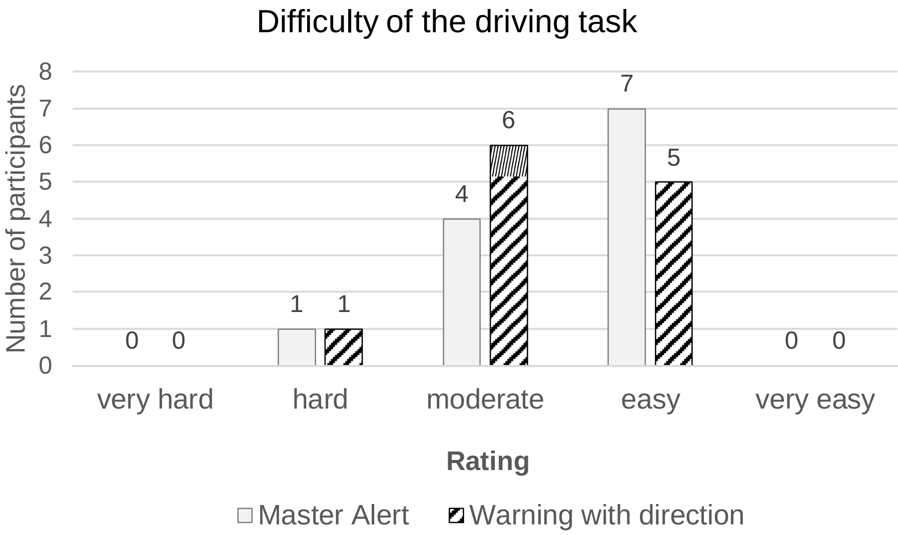


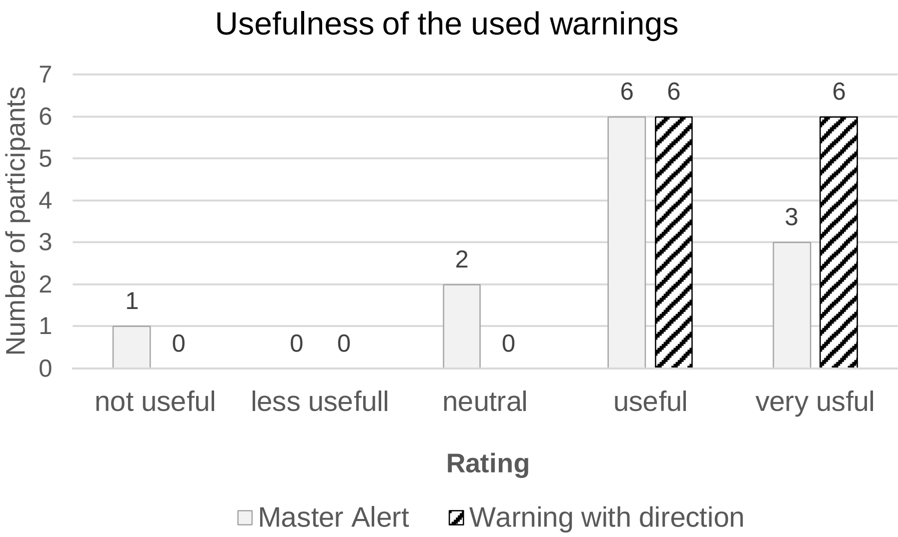
Figure 3.11: Maximum horizontal head rotation for false alarm scenarios regarding the warning schemes.

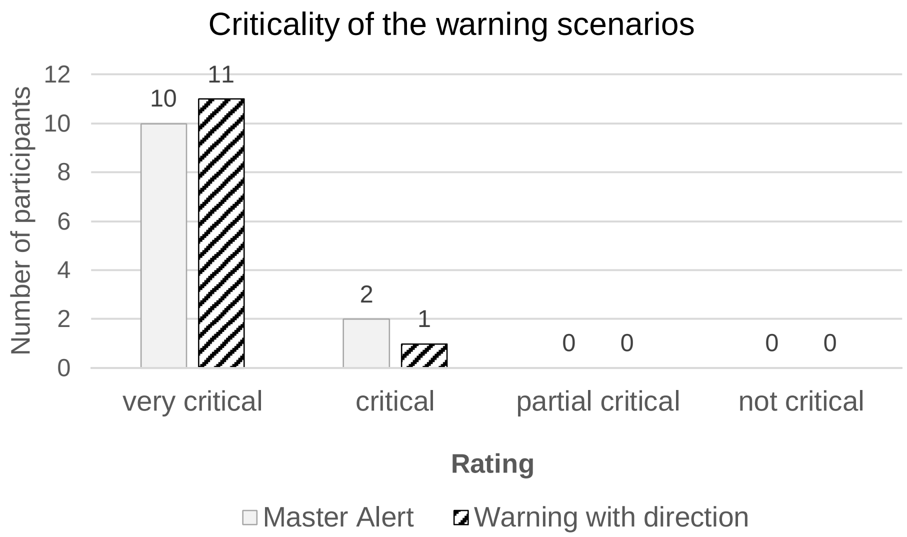
Participants of the group "warning with direction" (*M* = 30.46°) showed more head rotation than participants of the group Master Alert (*M* = 15.55°) for false alarms with warning direction, $t(46) = -2.05$, $p < .05$, mean difference of 14.91°, see Figure 3.11. It is important to notice that the Master Alert was not broadcast from different directions in both false alarm scenarios. Only warnings with direction were broadcasted from different directions in FA scenario with direction. Furthermore, the maximum head rotation did not differ for "Warning scheme" in false alarms without warning direction. Also the comparisons between false alarms with direction and false alarms without direction were not significant, $p > .10$.

3.3.2 Subjective Data

The following section focuses on subjective participant ratings and participant comments to open interviews. For each subjective scale Figure 3.12 illustrates individual histograms. Nearly all participants rated the difficulty of the driving task as moderate or easy, the warning as useful or very useful, and were satisfied with the quality of driving in test track, see Figure 3.12. The criticality of scenarios was rated very high. The subjective ratings of the Master Alert group and the group “warning with direction” did not differ.







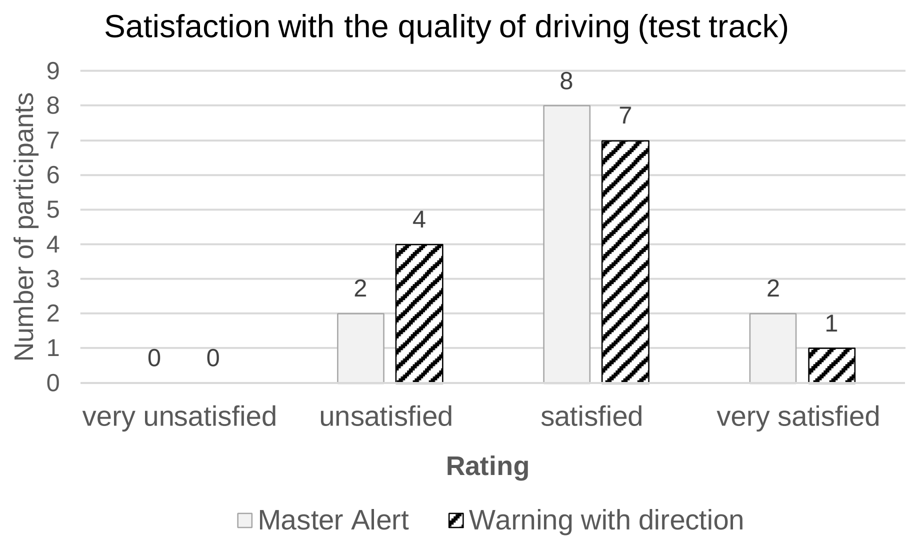


Figure 3.12: Histograms of assessed subjective scales. The figures show participant ratings for the difficulty of the driving task, the usefulness of the used warnings, the criticality of the warning scenarios and the satisfaction with the quality of driving in the test track, grouped by the warning scheme.

In a final interview 67% of the participants of the group “warning with direction” reported that they could hear the warning coming from multiple directions. Furthermore, 88% of the participants were not surprised that the same warning was used for very different scenarios. The warning was experienced as general alarming to increase attention. The prototypical driver response to warning was described as follows: 1) release of accelerator pedal 2) increased attention 3) braking reaction. The predictability of critical scenarios was rated as middle or low by 96% of participants. All participants mentioned the false alarms as an important aspect of the warning. 16% of participants described the warning as unpleasant but also described it as useful. Only one participant evaluated the warning as not useful and unpleasant.

3.3.3 Summary

The effects of two auditory warning schemes (Master Alert, warning with direction) were compared regarding participant responses in a rural test track, containing frontal and lateral hazards, and false alarm scenarios. Two randomly assigned participant groups were evaluated, one was alerted with an auditory warning which contained a warning direction cue, and the other group was alerted with an auditory Master Alert.

Effects of the factor "Warning scheme" (Master Alert, warning with direction) were found for **lateral scenarios**, in which the participants had to move their head right or left to spot the hazard early. Participants of group "warning with direction" visually fixated the hazardous object faster and showed more head rotation into hazard direction than participants of the group Master Alert. The accelerator pedal reaction times and the brake reaction times did not differ between the two warning schemes for lateral scenarios. Descriptively there is a tendency for participants of group "warning with direction" to show faster accelerator pedal reaction times and faster brake reactions times.

For **frontal scenarios**, in which the participants could respond to the critical situation by looking through the windshield (frontal), effects of "Warning scheme" were found for the first of six critical scenarios only. In this frontal collision scenario, participants of the group "warning with direction" showed slower brake reaction times than participants of the group Master Alert.

For **false alarms** on straight rural road sections, participants of the group "warning with direction" showed more head rotation than participants of the Master Alert group. Furthermore, **subjective scales** which evaluated the difficulty of the driving task, usefulness of the used warnings, the criticality of used scenarios as well as the driver performance, did not differ for the warning schemes. In general, participant rated the used warning scenarios as critical and hard to predict. Furthermore, nearly all participants rated the warnings as useful or very useful, but not always as pleasant.

3.4 Study 1 Discussion

Study 1 compared the effects of two auditory warning schemes (Master Alert, warning with direction) regarding participant responses in a rural test track containing frontal and lateral hazards. Twenty-four participants were assigned randomly to two groups, corresponding to the two warning schemes. All warnings had a warning onset of 3.9 TTA for lateral warning scenarios and 2.5 s of TTC for frontal warning scenarios.

According to the hypothesis, effects of the factor “Warning scheme” (Master Alert, warning with direction) were found for **lateral warning scenarios** in which participants were alerted to hazardous cross traffic. For these scenarios, the warning with direction assisted participants to focus their gaze 372 ms faster on the laterally hazardous objects compared to the Master Alert. Furthermore, the warning direction led to more intensive head rotation in direction of the hazards compared to the Master Alert, a mean difference of 10°. The head rotation also supports the faster fixation of hazardous objects because a more intensive head rotation was necessary to spot the pronounced lateral hazardous objects. These results are in line with studies which indicate that auditory direction cues can facilitate participant behavior in the context of driving (Fricke, 2009; Ho & Spence, 2009; Thoma, 2010).

The conducted interviews revealed that lots of participants were not aware of the auditory direction cuing effect. Only 67% of the participants in the group “warning with direction” noticed the direction of the warning at all. Additionally, many participants may have experienced the usefulness of the warning direction cues only in some of the driving scenarios. The auditory pre-test indicated that it was harder to distinguish the spatial position of the implemented auditory warnings, if they were broadcasted with large time intervals like in the test track. In this case, the driver could not use the last auditory warning as reference to determine the position of a new auditory warning.

The factor “Warning scheme” did not show an effect on accelerator pedal reaction times, brake reaction times and the number of collisions in lateral scenarios. Yet, descriptively, there was a tendency that warnings with direction led to slightly faster brake reactions times than the Master Alert. Moreover, there was large variance regarding the brake reaction times. This is an interesting finding because according to the process model and comparable studies with later warning onset (Ho & Spence, 2009; Thoma, 2010), a warning direction cue should affect the attention and also the driver’s response. If drivers perceive the hazardous objects earlier, they should be able to faster understand and anticipate the situations, and also faster select the right response. The results of Study 1 do not support this hypothesis. Different reasons may have led to the missing effect of the “Warnings scheme” on the accelerator pedal reaction times and brake reaction times. First, the early warning onset may have offered the participants enough time to choose very different times to start braking, which caused the large variance of brake reactions. Second, even if participants have perceived the hazards, they may not have anticipated the right effects of the hazards (e.g., Chan et al., 2010). In this context, participants may have perceived the scenarios as rather artificial or difficult to predict. This assumption is supported by participants’ comments. Some of them reported that they did not expect the hazard to enter the intersection without stopping. Furthermore, participants perceived the criticality of used hazards in different ways, which may have caused the large variance. For example, a motorbike was evaluated more critical than a car, and led to faster brake responses. A third reason for the missing effects of the warning schemes may be that drivers showed some kind of adapted driving behavior, which could not be covered by the analyzed measures. On average, BRTs of lateral scenarios were in the range of 838 to 1759 ms, which is about 500 ms above the mean reported TBT of collision mitigation studies using more imminent warnings (see section 2.2.3). Thus, it is very likely that the BRTs are mainly determined by the early warning onset and pronounced lateral setting of the scenarios of Study 1. Regarding this finding, additional measures may be needed to better analyze brake responses to early warnings.

Another interesting point is that participants often initialized braking slightly before they visually fixated and tracked the hazardous objects. The analysis of the video data revealed that drivers may have peripherally recognized the hazardous object before fixation and thus responded with a brake reaction before the following hazardous object fixation. These findings are supported by studies (e.g., Ho & Spence, 2009) which indicate that peripheral visual signals can be used to facilitate driver's responses.

In **frontal scenarios**, the participants' attention was already focused on the frontal scene before the warning, and participants could respond to the hazards without orienting their attention laterally. The factor "Warning scheme" showed no effect on the assessed measures in frontal scenarios. One exception was the first frontal warning scenario, in which participants who received the warning with direction showed slightly slower brake reaction times than the participants of the group Master Alert. This effect corresponds to Ho & Spence (2005) who discuss that auditory warnings which include a directional cue, may slow down initial responses but facilitate subsequent responses to the warning. Additionally, the questionnaires and interviews showed that participants perceived the Master Alert and the warning with direction as equally appropriate for frontal scenarios which covered two different necessary driver responses: steering and braking. These results are in line with the studies of Cummings et al. (2007), which also included Lane Departure Warning scenarios and Frontal Collision scenarios to examine a Master Alert. In this context, participants mentioned that they have to understand the reason for the warning, which was easy to identify in frontal scenarios. Thus, a Master Alert may be especially useful, if the environment directly provides the necessary cues to understand and anticipate the scenario.

According to the hypothesis, the factor "Warning scheme" showed an effect on the visual search behavior of participants in the **false alarm scenarios**. Participants of the group “warning with direction” on average showed 14.91° more head rotation to the left and the right, compared to the participants of the group Master Alert. This means that the auditory warning direction cue may also have directed participants gaze laterally, even if no hazardous object was present. The reason therefore can be the effectiveness of the auditory direction cue to orient the gaze and attention, or the head rotation response was learned (e.g., conditioned) in the lateral scenarios and applied to the false alarms scenarios. In contrast to the study of Herzberg (2012), participants showed no preference to the generic warning in false alarm scenarios. It is very likely that the used auditory direction cues were less obvious than visual direction cues in the head-up display, used by Herzberg (2012). Because many participants were not aware of the directionality of the false alarms in Study 1, they may not have evaluated the warning schemes differentially.

The warning schemes did not differ for the different assessed **subjective scales**. In general, the implemented warning scenarios were rated as critical and hard to predict. These ratings were intended through the scenario design and the possibility of collisions with the hazardous objects. Furthermore, nearly all participants rated the warnings as useful or very useful and were satisfied with their performance. Only three participants reported that they would not have needed the warnings, corresponding to a usefulness rating of moderate or not useful. These three participants had experience with ADAS, which may have influenced their evaluation. Overall, the subjective measures confirmed the effectiveness of both warning schemes (Master Alert, warning with direction). Moreover, no participant was surprised that only one warning was used for different scenarios. It is not clear why participants evaluate the Master Alert comparable to the warning with direction, but maybe the perceived differences between these warning schemes were too low. To address the low warning scheme distinguishability of Study 1 and to focus on the anticipation of the driver, Study 2 used visual and auditory warnings which include direction cues and object cues.

Study 1 confirmed the effectiveness of early auditory warning direction cues to facilitate the visual fixation of lateral hazards at intersections in comparison to an auditory Master Alert. These warning direction cues led to a more pronounced head rotation in the direction of lateral hazards and to more visual search behavior for false alarm scenarios. Due to large variance, no differences between the warning schemes regarding the accelerator pedal reaction times and the brake reaction times were found. Furthermore, the warning schemes did not differ for the warning acceptance, but overall, warnings were evaluated as useful and appropriate for different use cases.

4 Main Study 2

4.1 Study 2 Background

Regarding the warning process model (see section 2.1.2), Study 1 focused on the processing steps of attention and perception of the driver (warning receiver), to examine the effects of warning direction cues. Study 1 confirmed the effectiveness of warning direction cues to orient the driver's gaze and attention to relevant objects in lateral scenarios. In the next step, the warning processing stages of understanding and anticipation of the driver play an important role to explain what happens after attentional and perceptional processing. As discussed in Study 1, the fast perception of hazards by the driver may not necessarily lead to a fast driver response. It is very likely that driver anticipations may influence the latency and quality of driver responses to hazards. To further examine how anticipations can influence the driver's response to hazards, Study 2 includes warning object cues which can assist drivers in their process of understanding and anticipating. Thoma (2010) argued that object cues (specific warnings) may be especially effective if the environment does not provide enough information to understand or anticipate the hazardous situation, e.g. scenarios with covered hazardous objects and complex traffic. Especially for early warnings, hazards are difficulty to spot and to anticipate by the driver. Thus, object cues may assist the driver in adapting to the hazardous situation. To analyze driver responses to early ADAS warnings in detail and to distinguish between the effects of warning direction cues and warnings object cues, Study 2 uses four ADAS warning schemes which are the result of the manipulation of Warning direction (no direction, with direction) x Warning object (no object, with object).

A requirement to implement warning object cues is the usage of visual modality for the warning HMI (see section 2.4.2). Furthermore, it is indicated to use auditory warnings additionally, because visual information can be easily missed if the drivers are distracted (ISO, 2005). For the combined presentation of visual and auditory warnings, an auditory warning can alert the driver and suggest him to watch at the more complex visual warning. Moreover, the presentation of compatible, multimodal warning cues can facilitate driver responses, compared to a unimodal presentation (Lee & Spence, 2008). Thus, the warning direction cues of Study 2 are presented multimodal (auditory and visual) and the warning object cues visually.

A main reason for the missing effect of the warning schemes on the warning acceptance ratings of Study 1 may have been the perceived low distinguishability of the different auditory warning schemes. In contrast, a clearly perceivable visual variation of warning specificity should lead to an effect on the warning usefulness and ADAS acceptance. Furthermore, laboratory studies on visual attention (e.g., Posner, 1980) and driving simulator studies (e.g., Naujoks et al., 2012) have proven the effectiveness of object cues to direct human attention and facilitate participant responses (see section 2.3.3). Hence, a multimodal presentation of visual and auditory warning direction cues should assist the driver to fast and appropriately respond to possible hazards. Moreover, a visual warning object cue may help the driver to identify the hazardous object and anticipate its consequences (see section 2.1.2).

Findings on combined expectancies regarding selective attention suggest that the combination of spatial and object cues is effective to direct the attention and facilitate responses, yet, only if these cues have comparable validity. For Study 2 this requirement is met because the validity of direction and object cues is set equally. However, additive effects regarding the facilitation of driver responses are very unlikely for the combination of warning direction and warning object cues. The reason therefore is that the possible overall facilitation is limited by the corresponding cognitive processes and the needed time for possible action responses.

Most recent studies performed on generic ADAS warnings (Herzberg, 2012; Naujoks et al., 2012) used a head-up display to examine generic warnings. However, because of the costs, most small and compact cars will not be equipped with a head-up display in the near future. Furthermore, detailed findings to the usage of a free configurable cluster display regarding early collision warnings are missing. Thus, I decided to use a freely programmable cluster to display visual warnings for Study 2. Moreover, an early warning onset should offer the participants enough time to look at the cluster display and back to the driving scene. Consequently, the results of Study 2 should help to assess the usefulness of a cluster display for the implementation of early collision warnings.

In 2012 (Germany) about 31% of accidents with personal injury took place in complex driving scenarios, e.g. with turning, changing direction, reversing, leaving traffic and right-of-way scenarios, which were highly associated with urban traffic (Statistisches Bundesamt, 2013). Furthermore, urban scenarios offer more complexity to the driver, e.g. high traffic density and occlusions by buildings, compared to rural scenarios. To study how drivers can be assisted by early warnings in these scenarios and to increase the realism of scenarios, Study 2 focuses on lateral and frontal scenarios in an urban setting. A higher level of realism should also reduce the probability of inappropriate driver anticipations which may be caused by artificial scenarios. Furthermore, lateral and frontal scenarios were included in Study 2, to compare possible effects with Study 1. As for Study 1, effects of warning direction cues should predominantly be present in lateral warning scenarios of Study 2. To address typical hazards of urban scenarios, which will be detectable through technologies like C2X, Study 2 focuses on the following hazardous objects: cars, bikes, and pedestrians. For consistency, all critical scenarios cover hazardous objects which may cause a collision, corresponding to the ADAS cluster “warning of collisions”.

Altogether, a warning direction cue and/or warning object cue should facilitate the driver’s fixation of a hazard and assist him to adapt his behavior to an associated critical situation. Furthermore, these warning cues should increase the warning usefulness ratings compared to a generic warning because of the experienced usefulness and their visual salience.

In the context of urban scenarios with an early warning onset and high traffic complexity, it is probable that unnecessary warnings (UW) can occur (see section 2.1.3). For these scenarios, the high complexity of the situational analysis (ADAS side) can lead to a hazard classification of an object, which turns out as a neutral object. In these unnecessary warning scenarios, a specific warning may assist the driver to identify the cause of the warning and thereby reduce the inappropriate responses, e.g. braking responses without spotting the hazard. On the contrary, a generic warning would lead to more brake reactions because it is harder for the driver to identify which object was classified falsely as a hazard.

Compared to Study 1, measures of Study 2 were extended to examine driver responses to early warnings more detailed. Therefore, the situational criticality (minimum TTA / TTC) and the intensity of the participants' braking response (maximum brake pedal position) were assessed as well as the accelerator pedal reactions and the brake reactions associated with the TTA and TTC. These adapted measures should be more suited to explain the driver's behavior to early warnings, for example see Naujoks et al. (2012). To assess the warning usefulness more precisely in Study 2 in comparison to Study 1, participants evaluated warnings directly in the warning scenarios and also after driving in the test track. In addition to that, questionnaires and interviews were used to assess the desire to use and buy the experienced warning ADAS. A driving simulator with a complete Insignia mockup (model year 2012) was chosen (see section 4.2.4.1) to increase the realism and driver experience for Study 2.

Study 2 Hypotheses

Participants should benefit from a warning with direction cue as well as from a warning with object cue for their response to a hazard. Warnings with direction will decrease the time that drivers need to fixate hazards and increase warning usefulness ratings compared to warnings without direction. Warnings with object may also facilitate the time to hazard fixation and should increase warning usefulness ratings compared to warnings without an object. Furthermore, warnings with direction and warnings with object should lead to more situation adapted driver behavior compared to warnings without direction or warnings without an object. This situation adapted driver behavior will manifest in differences for the accelerator pedal reaction TTA / TTC, the brake reaction TTA / TTC, maximum brake pedal position and the minimum TTA / TTC. In general, effects of the factors "Warning direction" and "Warning object" should not be additive. Furthermore, effects of "Warning direction" and "Warning object" will be present for lateral scenarios and may occur less pronounced for frontal scenarios. For unnecessary warning scenarios, warnings with direction may lead to less brake reactions and higher warning usefulness ratings compared to warnings without direction. The same effect may occur for warnings with object compared to warnings without an object.

4.2 Study 2 Method

4.2.1 Preliminary Study

Jahns (2013) conducted a study for her Master thesis[12] that involved 20 participants. She compared two warning schemes, a generic warning without direction and without object cue and a specific warning that contained direction and object cue. For both warning schemes the warning onset was defined by a TTA / TTC of 3.8 s between ego-vehicle and location of possible collision. Aside the usage of only two warning schemes and two driving blocks, the method for the Master thesis was similar to the method of Study 2. Jahns (2013) found a subjective preference for the specific warning and an earlier hazardous object detection for the specific warning compared to the generic warning. Furthermore, specific warnings led to a later braking response compared to the generic warning. Based on the Master thesis, we improved the questionnaires, the instructions, the driving scenarios and eye-tracking calibration for Study 2. For Study 2 four driving

[12] The Master thesis of Martina Jahns was conducted under my supervision. The used questionnaires, driving scenarios and instructions were developed together.

blocks with individual warning scheme were implemented to examine the effects of "Warning direction" and "Warning object" in detail.

4.2.2 Driving Simulator Training and Participant Selection

To reduce symptoms of Simulator Sickness and preselect participants for the main study, a two-step simulator training was developed and conducted. In a qualitative pre-study with 6 participants we identified the following factors as most relevant to reduce Simulator Sickness: Reducing the intensity of visual pitching movements' feedback, avoiding the implementation of sharp curves and selecting a minimum distance of 2.6 m for buildings on the left and the right side of the road. These factors were confirmed by the low dropout rate[13] of the simulator training and the main study, see Figure 4.1.

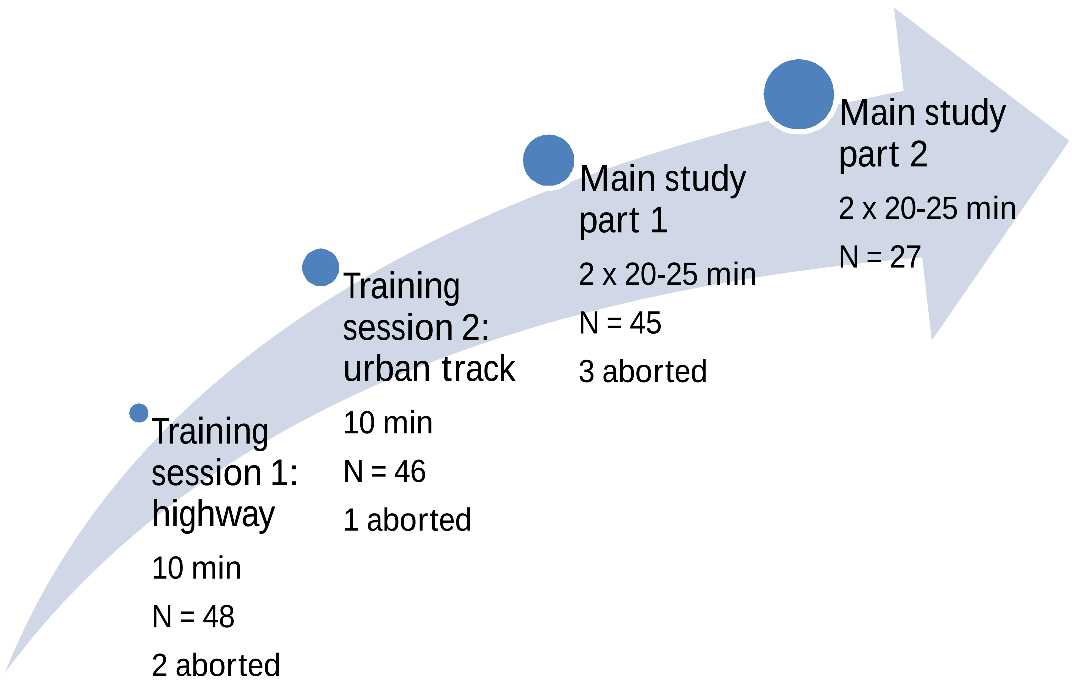


Figure 4.1: Overview of the conducted multistep participant training and the participant selection for Study 2. Participants had to pass two training sessions consisting of highway and urban tracks. After completing both training sessions they were allowed to drive in the main study. The number of participants and number of drop-outs are shown for each session.

Figure 4.1 shows an overview of the conducted participant training. In the first training session participants drove a highway track with increasing complexity, e.g. increasing traffic density, increasing number of curves and increasing number of

[13]Compared to other driving simulator test tracks with urban scenarios, e.g. Mourant & Thattacherry (2000).

obstacles. If participants were able to drive 10 minutes without having symptoms of Simulator Sickness, they were invited to a second training session. To assess symptoms of Simulator Sickness, selected questions of the Simulator Sickness Questionnaire (see section 2.7) were used and the participants monitored. In the second training session participants drove through an urban test track that included more complex situations than training session 1, e.g. right-of-way scenarios, pedestrian crossways, intersections with traffic lights, and more curves. If participants could also drive 10 minutes in training track 2 without having symptoms of Simulator Sickness, they were invited to start the main study. Overall 6 of 48 participants aborted the simulator training or the study. Forty-two participants completed the main study part 1. Five participants who completed the first part of the main study were assigned to test and improve the setup, but not invited to the second part of the main study. Ten participants had not the time to participate in the second part of the main study. The remaining 27 participants completed both parts of the main study.

Beside participant selection, the training helped participants to get familiar with the brake and steering wheel calibration of the driving simulator. This point was very important because brake reactions were one of the main measures of the main study.

4.2.3 Participant Sample

Twenty-seven normal hearing drivers with normal or corrected vision participated in both sessions of this experiment. Because of multiple interruptions, 3 participants were excluded. The resulting sample consisted of 24 participants (18 male) from different professional and educational levels (age of M = 32.8, SD = 9.3, 22 – 55 years). All participants were employees of the Adam Opel AG. Before participants started driving in the simulator, their health condition was assessed. Only participants in good health condition were allowed to drive in the simulator. Over the whole experiment participants could communicate with the experimenter by microphone and were able to take a break or to abort the study.

4.2.4 Apparatus

4.2.4.1 Simulator

Figure 4.2: Simulator of the Adam Opel AG which was used for Study 2.

The experiment was conducted on a fixed-base driving simulator of the Adam Opel AG, see Figure 4.2. A 130° FOV projection was implemented with three 70” TFT screens, each with a resolution of 1920x1080 pixels. As mockup a complete Insignia (model year 2012, Adam Opel AG) with automatic transition was used. Participants interfaced with the brake pedal, accelerator pedal and steering wheel. The speedometer, turning signals, seat adjustments were fully functional. Vehicular motor sounds and the alarm warnings were broadcast through a 6-channel audio system. Nine PCs (8x Intel I7 2600, 8x 3.40 GHz, 1x Intel Core I5-2500, 4x 3.3 GHz, 3 with NVIDIA GeForce GTX580, all with 4 GB Ram) and the SILAB software (WIVW GmbH) were used for simulation purposes. The PCs were connected by Gigabit-Ethernet. SILAB recorded data (e.g., vehicle dynamics, trigger signals) with a frequency of 60 Hz. An integrated cluster display (10” TFT) was used to display the speedometer, a timer and visual warnings.

Figure 4.3: Screenshot of the visual HMI which was used for the cluster display of Study 2. The particpants could always see the running timer and the speedometer. The warning HMI in the middle was only shown for the warnings in critical scenarios.

The experimenter could see the driver view and could control the simulation with the help of three 23" TFT displays. For eye-tracking a laptop with Dikablis System was also connected by Ethernet.

4.2.4.2 Eye-tracker

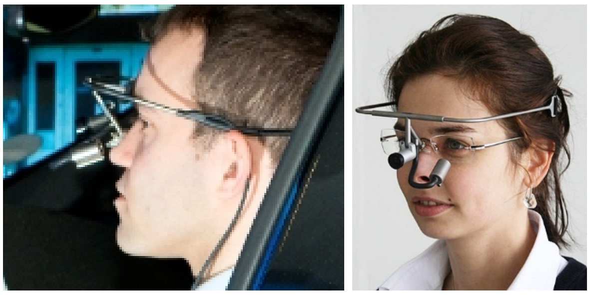


Figure 4.4: Dikablis eye-tracker which was used for Study 2.

For eye-tracking a head mounted Dikablis Eyetracking System (Ergoneers GmbH) was used. To track pupil movements and eye fixations, the Dikablis System uses an eye orientated IR camera and a field oriented color camera. The eye tracking data were recorded with a frequency of 25 Hz.

4.2.4.3 Questionnaires

In addition to a privacy statement and the startup check, participants had to fill out an evaluation questionnaire after each of four driving blocks, see Figure 4.5.

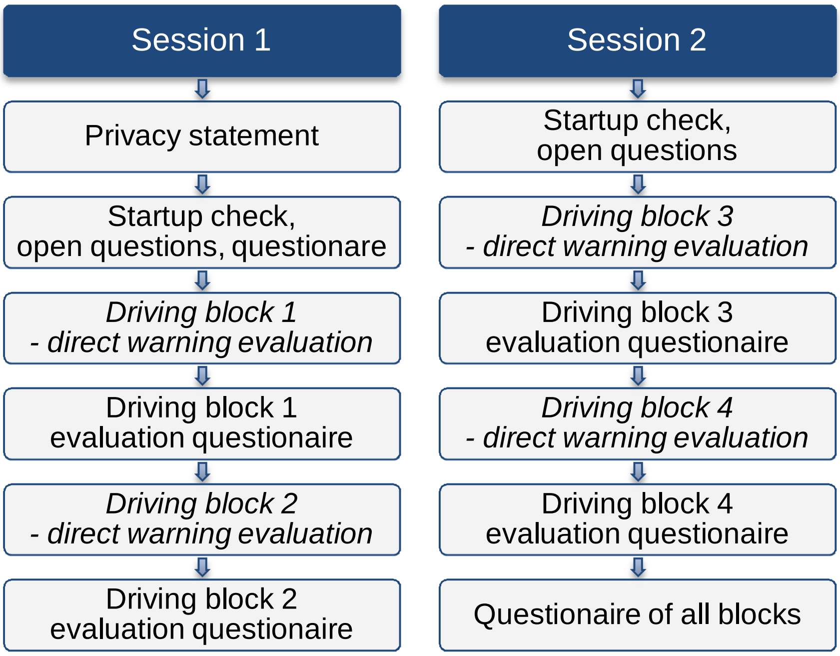


Figure 4.5: Overview of used questionnaires and open questions.

The startup check was made to assess participants driving experience, his or her health status and demographic variables. Participants evaluated the warnings twice. To assess driver ratings directly in warning scenarios, the simulation was frozen after participants responded to the scenarios by braking to stand (freeze-and-evaluate procedure). The participants were verbally asked the following three questions that were also used in the driving block evaluation questionnaire, see Figure 4.6.

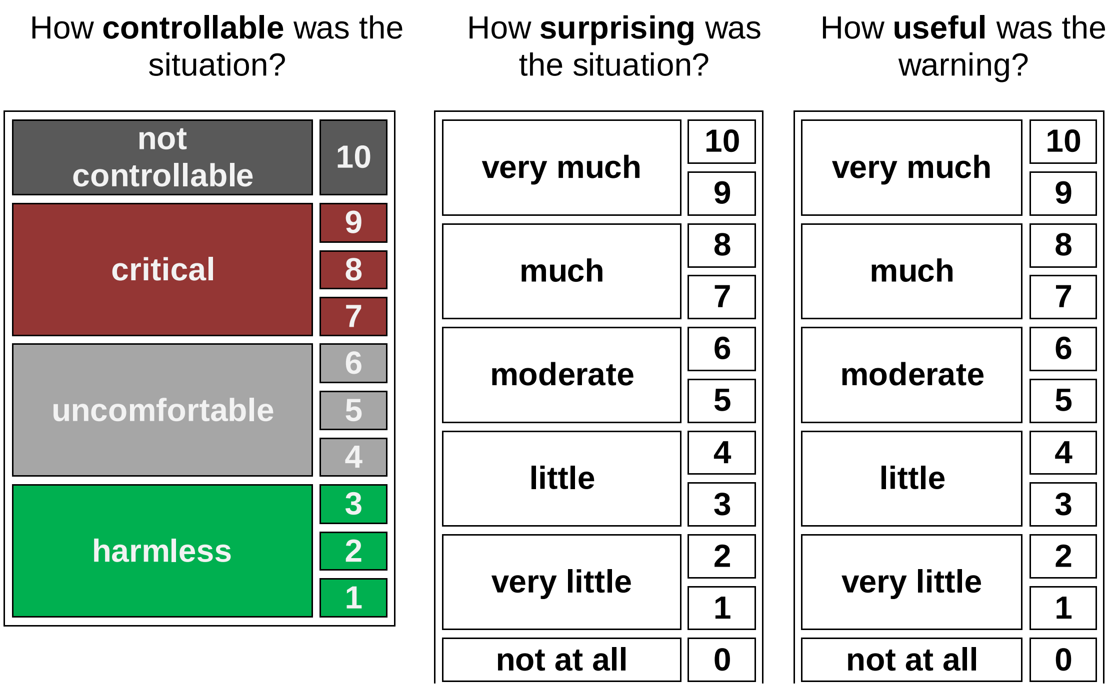


Figure 4.6: Subjective scales that were evaluated directly in the warning scenarios. The figure illustrates a translation of the used German scales.

The controllability scale, the scale of surprise in critical situations and the scale of usefulness of warning were adapted based on Naujoks, Grattenthaler and Neukum (2012). In case participants did not brake to standstill, e.g. unnecessary warnings, the experimenter asked them to brake and froze the simulation. The printed scales were mounted inside the car, near the center stack, to assist participants in scale usage.

In addition, participants evaluated the warnings after the driving block. The same questions as for the direct ratings were used, but grouped by hazard type (car, bike, and pedestrian). The direct warning ratings and the warning ratings after the driving block were used to asses and compare the warning usefulness for single scenarios and also the overall warning usefulness for different warning schemes and hazards. Furthermore, the typical driver response to warnings, willingness to buy and willingness to use the warning ADAS were evaluated. To better remember the different warning situations, a sheet with screenshots of warning situations and the warning schemes were handed over to the participants.

4.2.5 Experimental Design

A three within-subjects factor design with the factors “Warning object” x “Warning direction” x Scenarios was used for Study 2. Subsequently these three within-subjects factors are described.

4.2.5.1 Warning Object and Warning Direction

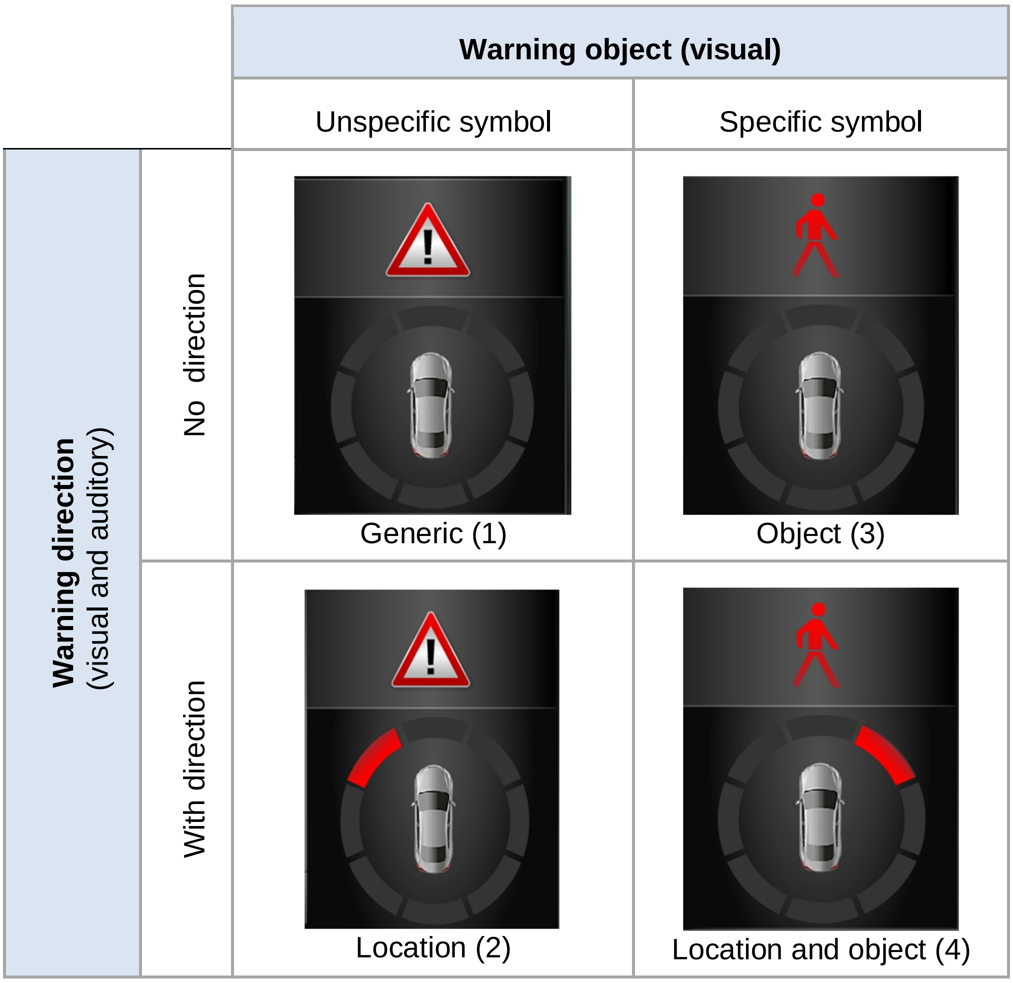


Figure 4.7: Four warning schemes based on the combination of the factors “Warning object” x “Warning direction”. The warning schemes were implemented as 4 warning HMI variants.

To manipulate the warning specificity, the within-subjects factors “Warning direction” and “Warning object” were implemented with 4 different visual HMIs[14] to the instrument cluster, see Figure 4.7. The warning scheme “generic“ (1) included no warning direction and warning object cues and showed only a generic warning icon. The warning scheme “location” (2) included warning direction cues (red segments) and no warning object cues (generic icon). The warning scheme “object” (3) included no warning

[14]The visual HMI was developed with help of Kersten Stahl (Adam Opel AG).

direction cues, but showed warning object cues (hazard icons). The warning scheme “location and object“ (4) included warning direction cues (red segments) and warning object cues (hazard icons). To generate the warnings the software Adobe Flash was used. Each visual warning was accompanied by an auditory warning with medium-high criticality. For warning schemes with location information (location, location and object), the auditory warning was broadcasted from the corresponding hazard direction. The used auditory warnings had following characteristics[15]: two-tone pulse with a duration of 300 ms, frequency of 1500 Hz, amplitude modulation of frequencies of 35 Hz, modulation depth 50%, attack-length 5 ms with linear increase, release-length of 265 ms with exponential decrease and interpulse interval of 30 ms.

According to the 4 warning schemes, 4 driving blocks were implemented. The order of the driving blocks was fully permuted, thus each of the participants drove one of 24 driving block sequences, see Figure 4.8. Because of the overall duration the experiment was 3 hours per participant, it was separated into 2 sessions.

[15]The auditory warnings were designed with help of Oliver Jung (Adam Opel AG).

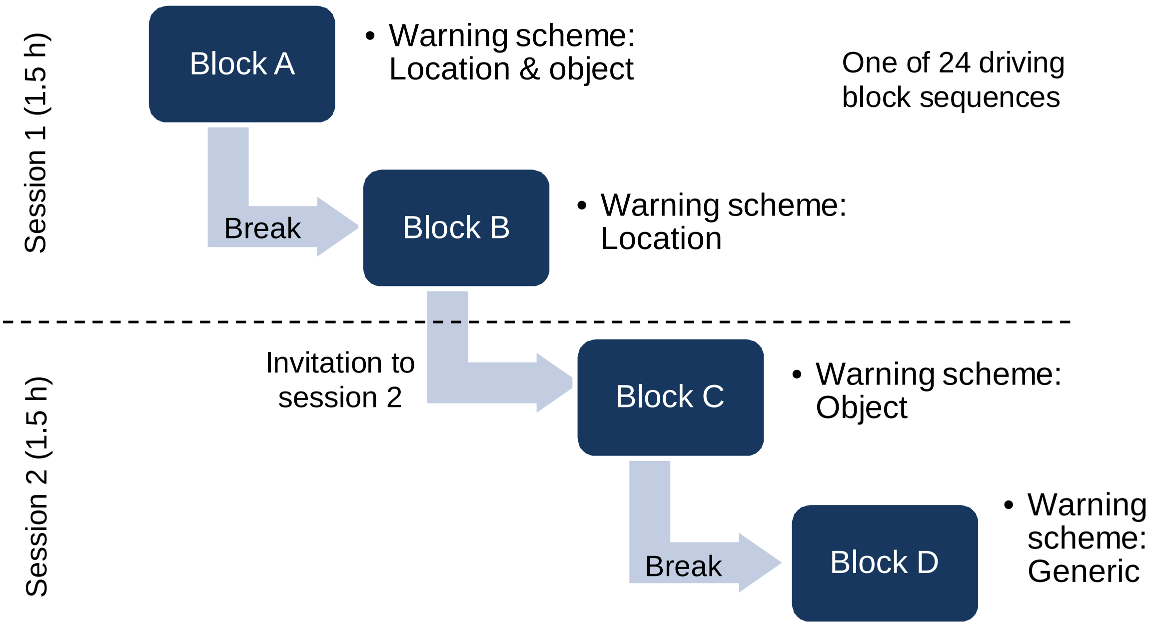


Figure 4.8: Example for a driving block sequence of Study 2. One of 24 driving block sequences is shown. Through full permutation of 4 driving blocks Study2 contained 24 driving block sequences.

4.2.5.2 Warning Scenarios

Warning scenarios with 3 different hazardous objects (pedestrian, car, bike) approaching from 3 locations (right, left, front) were implemented, see Figure 4.9. Scenarios including hazard approaching from right or left will be referred as lateral scenarios.

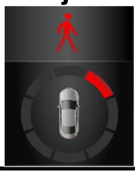
Warning scheme / driving block	*Hazardous object*	*Hazard location*		
		Lateral		
		Right	Left	Frontal
Location and object 	Pedestrian	X / UW	X	
	Car	X / UW	X	X
	Bike	X	X / UW	X
Location 	Pedestrian	X	X	
	Car	X	X / UW	X / UW
	Bike	X	X	X / UW
Object 	Pedestrian	X / UW	X	
	Car	X	X / UW	X
	Bike	X / UW	X	X
Generic alert 	Pedestrian	X	X / UW	
	Car	X	X	X / UW
	Bike	X / UW	X	X

Figure 4.9: Study plan and overview of warning scenarios, including unnecessary warnings (UW). Warning scenarios for 3 different hazardous objects (pedestrian, car, and bike) and 3 hazard locations (right, left, and frontal) were implemented. In addition to that, three unnecessary warning scenarios were assigned to the hazardous objects and the locations for each of 4 warning schemes.

For each of 4 driving blocks, 8 critical warning scenarios and 3 unnecessary warning scenarios were implemented, see Figure 4.9. Lateral scenarios were applied for the hazardous objects: pedestrian, car and bike. For frontal scenarios no pedestrian was used as hazard because pedestrians usually start to move from right or left side of the road before approaching the center of the lane. Unnecessary warning scenarios were pseudo randomly assigned to hazard type and location to minimize the scenario predictability. To compare effects of “Warning direction” and “Warning object”, the critical warning scenarios were implemented similarly in all driving blocks (angle, speed of hazardous objects). Thus only the environmental factors were changed for the critical scenarios between the driving blocks, e.g. buildings, trees, traffic. For all warning scenarios the warning onset was defined with a TTA (lateral scenarios) and TTC (frontal scenarios) of 3.8 s for the distance between participant's car and possible collision with the hazardous object. A modified SILAB script of the WIVW GmbH was used to measure the TTA and TTC

In all critical warning scenarios participants had to brake to avoid a collision, see Figure 4.10. The timing and traffic in warning scenarios, e.g. oncoming traffic, were designed to force participants to a braking response and eliminated possibilities for evasion maneuvers. In cases the hazardous object location was left or right, an angle of +/-36°, between center of frontal view and hazardous object, was implemented. For these lateral scenarios the hazardous object starting speed was set to 2 m/s for running pedestrian, 12 m/s for cars and 7.5 m/s for bikes. For frontal scenarios the angle between the center of the frontal view and the hazardous object was smaller than +/-20° and the hazardous object speeds smaller than 11 m/s. By approaching the location of the possible collision between ego-vehicle and hazardous object, the hazardous objects decreased their speed and stopped for 1.5 seconds to force the participants to brake.

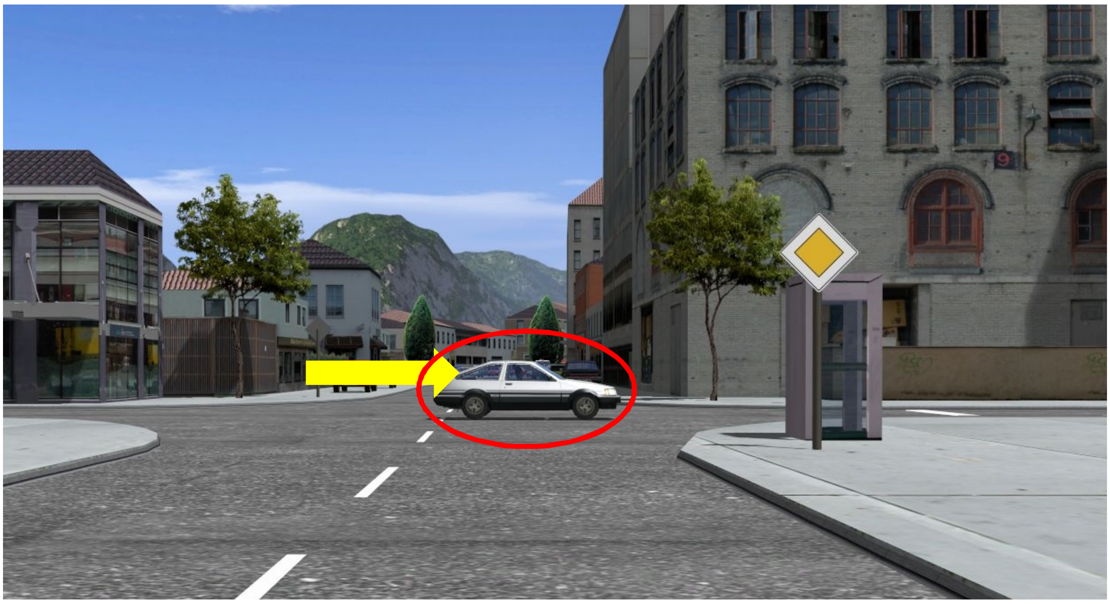


Figure 4.10: Example of lateral scenario with a hazardous car approaching from left side. The yellow arrow indicates the direction from which the hazardous car approaches. The illustration does not show surrounding traffic which was also included for this scenario.

In unnecessary warning scenarios, a warning of a possible hazardous object was broadcast. With progressing situation this object turned out to be neutral. For example a bike was driving from the right side of the road on a pedestrian walk into the direction of the lane center. Before the bike was entering the road, it abruptly turned and drove along the pedestrian walk, see, Figure 4.11.

Figure 4.11: Example of unnecessary warning scenario with a bike approaching from the right side. The yellow arrows indicates the direction from which the bike approaches and continues to drive.

4.2.6 Test Track

The test track consisted of four parts corresponding to the four warning schemes. Participant needed 20 to 25 minutes to complete one part. Each participant had to drive two parts in each of two sessions. An urban environment with many X-intersections, straight road parts and slight curves was used. The main road type consisted of two lane urban roads. In each of the four driving blocks the track started at the city entry and ended at an airport parking lot. To standardize speed and timings for the used scenarios, the maximum speed was locked to 50 kph. Participants had to constantly hold the accelerator pedal with middle force to maintain the speed of 50 kph. At the beginning of each driving block, a neutral scenario with a pedestrian walking over a pedestrian crossing was used to make the participants familiar with braking responses. All over the track random traffic with middle traffic density was simulated, including leading vehicles, oncoming traffic, and vehicles entering intersection from right or left. To avoid effects of tiredness, participants had to regulate their speed at intersections, curves and to leading vehicles. Many neutral scenarios with similar environment as for warning scenarios were implemented to reduce the predictability of warning scenarios.

4.2.7 Experimental Procedure

The main experiment consisted of two experimental sessions, each with a duration of approximately 1.5 h. In the first session, the participants were informed about the experiment procedure and had to write a privacy statement that covers the usage of data from eye-tracking, driving dynamics, interviews and questionnaires. After a startup check and the completion of a questionnaire, the eye-tracker was calibrated for 15 minutes. The eye-tracker calibration procedure was repeated for each driving block.

Then participants were informed that they will drive through an urban test track with an integrated warning system that displays warnings in the cluster display and outputs warning tones. Participants were told to only brake or overtake if it is necessary and maintain the 50 kph. As further instructions participants were told to get to the airport to catch a plane as fast as possible but also to stay in the legal speed limit. A timer in the cluster illustrated the running time, see 4.2.4.1. Participants were also instructed how to use 3 scales that were verbally questioned in each warning scenario.

After driving about 25 minutes through the urban test track and responding to 11 warning scenarios, participants arrived at an airport parking lot. Participants evaluated driving block 1 and proceeded with the second one. Driving block 2 was similar like driving block 1 but used another warning scheme, see 4.2.5.1. At the end of session one, participants evaluated driving block 2. Beside the instructions the same procedure as in session 1 was used for session 2. Thus, each participant drove through 4 driving blocks and experienced 4 warning schemes. At the end of session 2 participants were interviewed regarding the study and the used HMI.

4.2.8 Dependent Variables

For Study 2 we developed a method, the simulation freeze-and-evaluate procedure see 4.2.4.3, which was used to assess participant ratings directly in the warning situations. Compared to Study 1, these direct ratings were an improvement, because the evaluation of warnings was assessed directly after the warning situation. Thereby, participants could easily remember the warnings. Furthermore, a script[16] was implemented that exactly measured the TTA and TTC. The TTA was calculated between the positions of the participant’s car and the location of the possible collision with a hazardous object. A low TTA indicates a close distance to the hazardous object. One advantage of the TTA was the comparability to other studies (e.g., Naujoks, 2013; Naujoks et al., 2013). For frontal scenarios, the TTC was used instead of the TTA, because the TTC is suited for longitudinal traffic (see section 2.2.3). Consequently the dependent variables from vehicle data of Study 2 were stated in TTA or TTC and not in reaction times like for Study 1.

The following dependent variables of eye tracking data were analyzed:

- Time of hazardous object fixation (ms)

  Criteria: Time after warning HMI fixation until participants fixated the hazardous object in critical scenarios. The fixation time was determined by manual inspection of the eye-tracking data and vehicle data.
- Time of HMI fixation (ms)

  Criteria: Time after warning onset until participants fixated the visual warning HMI.
- HMI fixation duration (ms)

[16] The Script was written by the WIVW GmbH and adapted by me. For Study 1 this TTA-script was not yet available.

Criteria: Duration participants looked at the visual warning HMI.

The following dependent variables of vehicle data were analyzed:

- Accelerator pedal reaction TTA / TTC (s)

  Criteria: TTA / TTC after warning onset when the accelerator pedal was released completely.

- Brake reaction TTA / TTC (s)

  Criteria[17]: TTA / TTC after warning onset until 2% of the mean, maximum braking pressure of all participants was reached. All brake responses where addressed by these criteria.

- Maximum brake pedal position[18] (percent)

  Criteria: Maximum brake pedal position after warning onset.

- Minimum TTA / TTC (s)

  Criteria: Minimum TTA / TTC after warning onset. Low values indicate a close distance to the hazardous object. To identify possible collisions values smaller than 1 were analyzed in detail.

- Number of collisions with hazardous objects

  Criteria: Number of all collisions with hazardous objects, including slight and serious collisions.

- Number of braking reactions for unnecessary warnings

  Criteria[1]: Absolute number of brake reactions for unnecessary warning scenarios. Only brake reactions that reached 2% of the mean, maximum braking pressure of all participants were included.

Following dependent variables from direct ratings in warning scenarios were analyzed:

- Usefulness of warnings (10 point scale, from not useful at all to very much useful, see 4.2.4.3)

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[17] I chose 2% as criteria to ensure that all brake reactions are over the recording noise level.

[18] A peak-analysis of brake pedal position showed no additional effects. In nearly all cases the maximum brake pedal position was equal to the first peak.

I focused on the usefulness of warnings from the direct participant ratings in warning scenarios because they were most relevant for the hypothesis. Furthermore, the results of other direct participant ratings showed the same effect pattern as the usefulness of warning.

Following selected subjective scales and comments of questionnaires were analyzed:

- Usefulness of warnings grouped by hazardous object (10 point scale, from “not useful at all” to “very useful”: see section 4.2.4.3)
- Trust in system (10 point scale, very low to very high)
- Willing to pay for the warning system (Euro)
- Preference to use warning system in one's own car (4-point scale, from “not at all” to “yes sure”)
- Open questions and interview: participant’s comments to the warning schemes and study.

4.2.9 Data Preparation

Dependent variables of vehicle data and eye-tracking were pre-processed with Matlab and used for further analysis. All eye tracking videos of warning scenarios were inspected frame-by-frame to encode used dependent eye tracking variables. For further data processing and analysis the software D-Lab, Matlab, SPSS and Excel was used. For all dependent variables only trials with following criteria were included: the participants should not fixate and respond the hazardous object before watching the visual warning HMI, but the visual HMI has to be fixated. These criteria were applied to measure the maximized effect of the used warnings without the influence of clear expectations about the hazard. Following number of trials was excluded by the filter criteria for the four warning schemes: for location and object 4%, for direction 12%, for object 14% and for generic 15%. For the further analysis the missing trials were replaced with corresponding means of each condition.

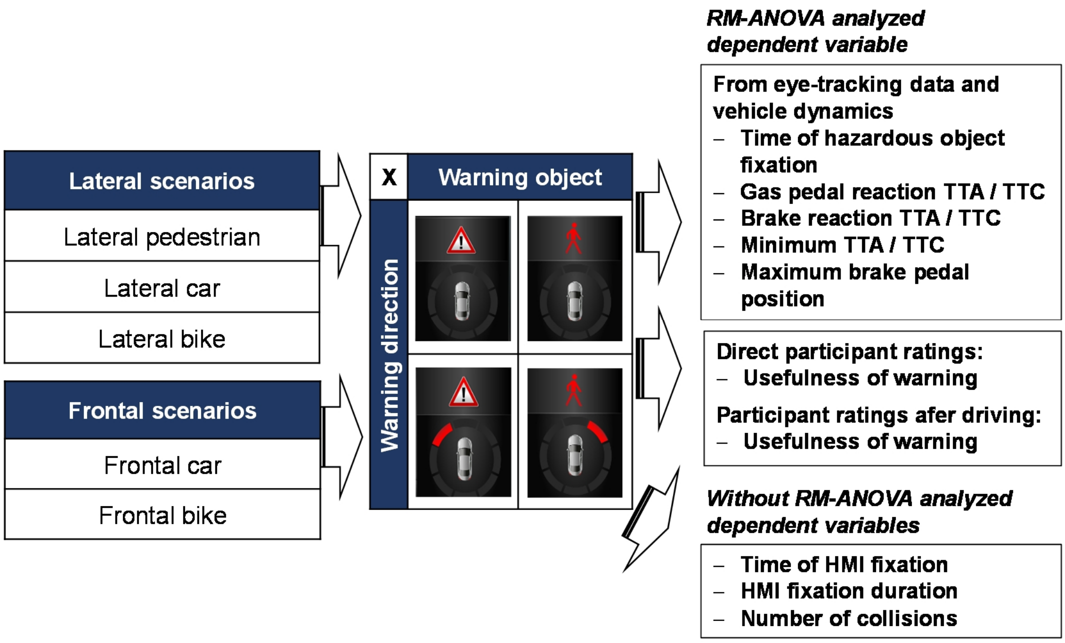

Figure 4.12: Overview of analyzed dependent variables for critical warning scenarios. Lateral and frontal scenarios were analyzed separately. For the warning schemes, the within-subjects factors "Warning direction" and "Warning object" were examined. Consequently, the RM-ANOVAs analyzed "Warning direction", "Warning object" and "Hazardous object" for frontal and lateral scenarios.

Figure 4.12 shows an overview of the analysis of critical warning scenarios of Study 2. Lateral scenarios, which included left and right scenarios, and frontal scenarios were analyzed separately. Following variables were analyzed with RM-ANOVAs using the within-subjects factors "Warning direction" (no direction, with direction) x "Warning object" (no object, with object) x "Hazardous object" (pedestrian, car, bike): time of hazardous object fixation, accelerator pedal reaction TTA / TTC, brake reaction TTA / TTC, maximum brake pedal position, the minimum TTA / TTC and the usefulness of warning. The TTA was used for lateral scenarios, the TTC for frontal scenarios. Furthermore, the factor "Hazardous object" did not include pedestrians for frontal scenarios (see section 4.2.5.2). The time of HMI fixation and HMI fixation duration was aggregated over all hazardous objects and compared with *t*-tests for dependent samples for the warning scheme. The aggregation was applied because a pretest indicated no difference between the different hazardous objects. Furthermore, collisions were only analyzed descriptively because they occurred rarely.

Critical warning scenarios and unnecessary warnings were analyzed separately. For unnecessary warning scenarios, I inspected the number of brake reactions, the time of HMI fixation, and the HMI fixation duration. I analyzed the number of braking reactions descriptively because the hazard type and hazard direction differed between the 4 driving blocks for unnecessary warnings. Furthermore, not all participants braked to stand in unnecessary warning scenarios. To compare means for each warning scheme for the time of HMI fixation and HMI fixation duration, *t*-test for dependent samples were conducted. The same *t*-test procedure was applied to the subjective scales of questionnaires.

The significance level for statistical calculations was set to $\alpha = .05$. The RM-ANOVA requirement of normal distribution was tested with Kolmogorov-Smirnov-Tests. The RM-ANOVA requirement of equable error variances was checked with a Levene´s-Test and a significance level of $\alpha > .20$. In cases a Mauchly's test for sphericity indicated that the sphericity assumption was not set, a Huynh-Feldt correction of degrees of freedom was applied. Interaction effects were examined with *t*-tests for dependent samples.

4.3 Study 2 Results

In the following, results of behavioral variables of eye-tracking and vehicle data are shown (see section 4.3.1). Then I will present the results of direct ratings of warning usefulness as well as the results for warning ratings after driving. For the behavioral variables and the direct ratings of warning usefulness, results are grouped by scenario types: lateral scenarios, frontal scenarios and unnecessary warning. To analyze the main variables, RM-ANOVAs[19] with the within factors “Warning direction”, “Warning object” and “Hazardous object” were used. At last section 4.3.4 shows the results of questionnaires and interviews for the comparison of implemented warning schemes (see

[19]The procedure to analyze the dependent variables with RM-ANOVAs is described in detail in section 4.2.9.

section 4.2.5.1). For all result figures of Study 2, the standard error (SE) is used for the error bar indicator. Some figures use the warning scheme names as variable-captions. The warning scheme names are a result from the combination of "Warning direction" and "Warning object": location and object (with direction, with object), location (with direction, no object), object (no direction, with object), generic (no direction, no object).

4.3.1 Behavioral Data

In the following, results of dependent variables regarding eye-tracking and vehicle data are shown. These results are grouped by scenarios types: lateral scenarios, frontal scenarios and unnecessary warnings. For each scenario group, I show first the results of all variables that were analyzed with RM-ANOVAs. Subsequently, I present the results of time to HMI fixation and HMI fixation duration as well as the number of collisions.

4.3.1.1 Lateral Scenarios

The factor "Warning direction" showed a main effect on all analyzed dependent variables, see Table 4.1. "Warning object" only led to a main effect on minimum TTA. For "Hazardous object" all dependent variables showed a main effect, except the accelerator pedal reaction TTA.

The interaction "Warning direction" x "Warning object" was significant for time to hazard fixation, brake reaction TTA, minimum TTA, and marginal significant for accelerator pedal reaction TTA, see Table 4.2. The interaction "Warning direction" x "Hazardous object" showed an effect on all dependent variables, except the maximum brake pedal position. Furthermore, "Warning object" x "Hazardous object" showed an effect on all dependent variables, except the time to hazard fixation. The triple interaction "Warning direction" x "Warning object" x "Hazardous object" showed an effect on all dependent variables. In the following, the main effects and interaction effects are described separately for each dependent variable.

Table 4.1: Main effects on behavioral variables of lateral warning scenarios

Dependent variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Hazardous object (ped., car, bike)
Time to hazard fixation	$F(1,23) = 17.79$, **$p < .001$****, $\eta_p^2 = .44$	$F(1,23) = .94$, $p = .34$, $\eta_p^2 = .04$	$F(2,23) = 48.86$, **$p < .001$****, $\eta_p^2 = .68$
Accelerator pedal reaction TTA	$F(1,23) = 33.23$, **$p < .001$****, $\eta_p^2 = .59$	$F(1,23) = .68$, $p = .42$, $\eta_p^2 = .03$	$F(2,23) = 3.06$, $p = .06$, $\eta_p^2 = .12$
Brake reaction TTA	$F(1,23) = 75.63$, **$p < .001$****, $\eta_p^2 = .71$	$F(1,23) = .61$, $p = .44$, $\eta_p^2 = .03$	$F(2,23) = 4.75$, **$p < .05$***, $\eta_p^2 = .17$
Maximum brake pedal position	$F(1,23) = 5.07$, **$p < .05$***, $\eta_p^2 = .18$	$F(1,23) = .72$, $p = .40$, $\eta_p^2 = .03$	$F(2,23) = 4.40$, **$p < .05$***, $\eta_p^2 = .16$
Minimum TTA	$F(1,23) = 21.18$, **$p < .001$****, $\eta_p^2 = .48$	$F(1,23) = 8.57$, **$p < .01$****, $\eta_p^2 = .27$	$F(1,23) = 11.74$, **$p < .001$****, $\eta_p^2 = .34$

Table 4.2: Interaction effects on behavioral variables of lateral warning scenarios

Dependent variable	Warning direction x Warning object	Warning direction x Hazardous object	Warning object x Hazardous object	Warning direction x Warning object x Hazardous object
Time to hazard fixation	$F(1,23) = 50.17$, **$p < .001$****, $\eta_p^2 = .69$	$F(2,46) = 7.99$, **$p < .01$****, $\eta_p^2 = .26$	$F(2,46) = .387$, $p = .681$, $\eta_p^2 = .017$	$F(2,46) = 27.19$, **$p < .001$****, $\eta_p^2 = .54$
Accelerator pedal reaction TTA	$F(1,23) = 3.94$, $p = .06$, $\eta_p^2 = .15$	$F(2,46) = 8.23$, **$p < .01$****, $\eta_p^2 = .26$	$F(2,46) = 5.67$, **$p < .01$****, $\eta_p^2 = .20$	$F(2,46) = 3.27$, **$p < .05$***, $\eta_p^2 = .12$
Brake reaction TTA	$F(1,23) = 7.03$, **$p < .05$***, $\eta_p^2 = .23$	$F(2,46) = 11.14$, **$p < .001$****, $\eta_p^2 = .11$	$F(2,46) = 5.96$, **$p < .01$****, $\eta_p^2 = .23$	$F(2,46) = 4.66$, **$p < .05$***, $\eta_p^2 = .17$
Maximum brake pedal position	$F(1,23) = .94$, $p =.34$, $\eta_p^2 = .04$	$F(2,46) = 2.73$, $p =.08$, $\eta_p^2 = .04$	$F(2,46) = 4.63$, **$p < .05$****, $\eta_p^2 = .17$	$F(2,46) = 3.23$, **$p < .05$***, $\eta_p^2 = .12$
Minimum TTA	$F(1,23) = 17.74$, **$p < .001$****, $\eta_p^2 = .44$	$F(2,46) = 16.54$, **$p < .001$****, $\eta_p^2 = .42$	$F(2,46) = 17.11$, **$p < .001$****, $\eta_p^2 = .43$	$F(2,46) = 19.87$, **$p < .001$****, $\eta_p^2 = .46$

Time to hazard fixation. The main effect of “Warning direction” led to 170 ms faster hazardous object fixation for warnings with direction, compared to warnings without directions. The main effect of “Warning direction” was modified by the interaction “Warning direction” x “Warning object” x “Hazardous object”. Figure 4.13 illustrates this interaction effect. For warnings without object, the warning with direction led to faster hazardous object fixation than for warnings without direction, for hazardous pedestrians, 194 ms, $t(23) = 1.89$, $p < .01$, $d = .39$, for hazardous car, 290 ms, $t(23) = 3.70$, $p < .01$, $d = .756$, and for hazardous bike, 936 ms, $t(23) = 8.82$, $p < .001$, $d = 1.80$. In contrast, for warnings with object the warning with direction led to slower hazardous object fixation than for warnings without direction, 135 ms for hazardous pedestrian, $t(23) = 2.35$, $p < .05$, $d = .48$, 198 ms for hazardous bike, $t(23) = 2.18$, $p < .05$, $d = .44$, and not significant for hazardous car, $p > .10$.

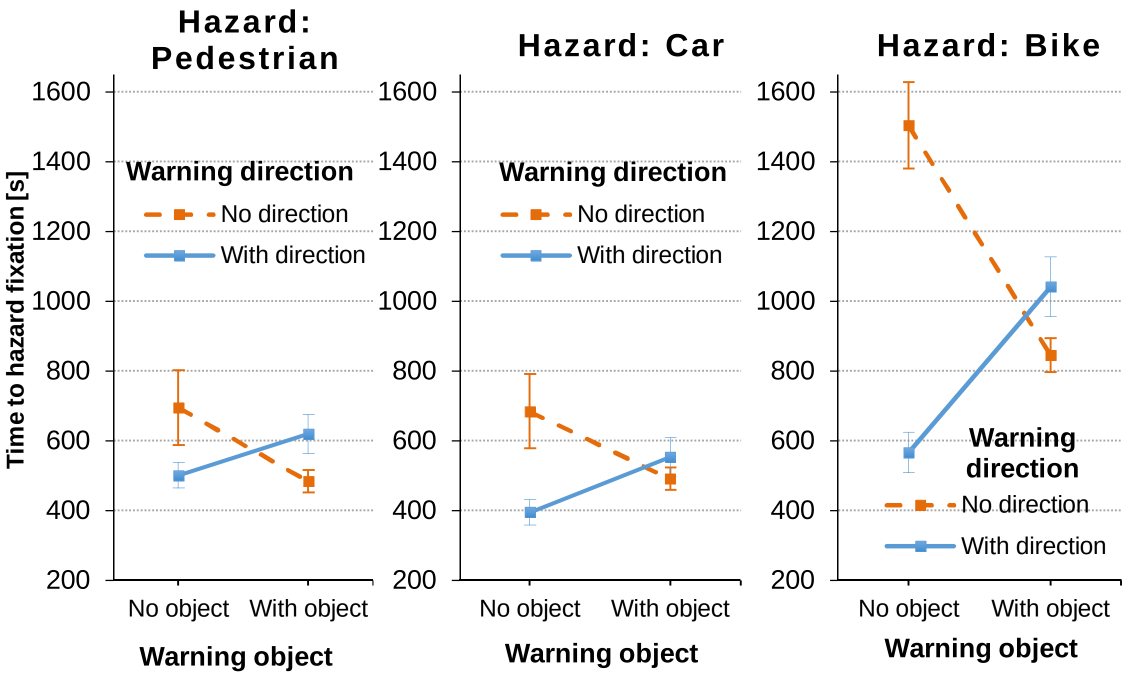

Figure 4.13: Interaction between “Warning direction” and “Warning object” on the time to hazardous object fixation of lateral scenarios grouped by “Hazardous object”.

Accelerator pedal reaction TTA. The main effect of “Warning direction” led to 159 ms smaller accelerator pedal reaction TTA for warnings with direction compared to warnings without direction. A smaller accelerator pedal reaction TTA indicates that participants responded at a closer distance to the hazardous object, in other words, participants responded later.

The main effect of “Warning direction” was modified by the interaction “Warning direction” x “Warning object” x “Hazardous object”. Figure 4.14 illustrates this interaction effect. The main effect of “Warning direction” was confirmed for hazardous pedestrians, $t(23) = 5.22$, $p < .001$, $d = 1.07$, and hazardous cars, $t(23) = 5.74$, $p < .001$, $d = 1.17$. In hazardous bike scenarios, the warning with direction led also to smaller accelerator pedal reaction TTA than for warnings without direction, 221 ms $t(23) = 3.62$, $p < .01$, $d = .73$, yet, only when combined with warnings with object. For warnings without object in hazardous bike scenarios, warnings with direction and warnings without direction did not differ, $p > .10$.

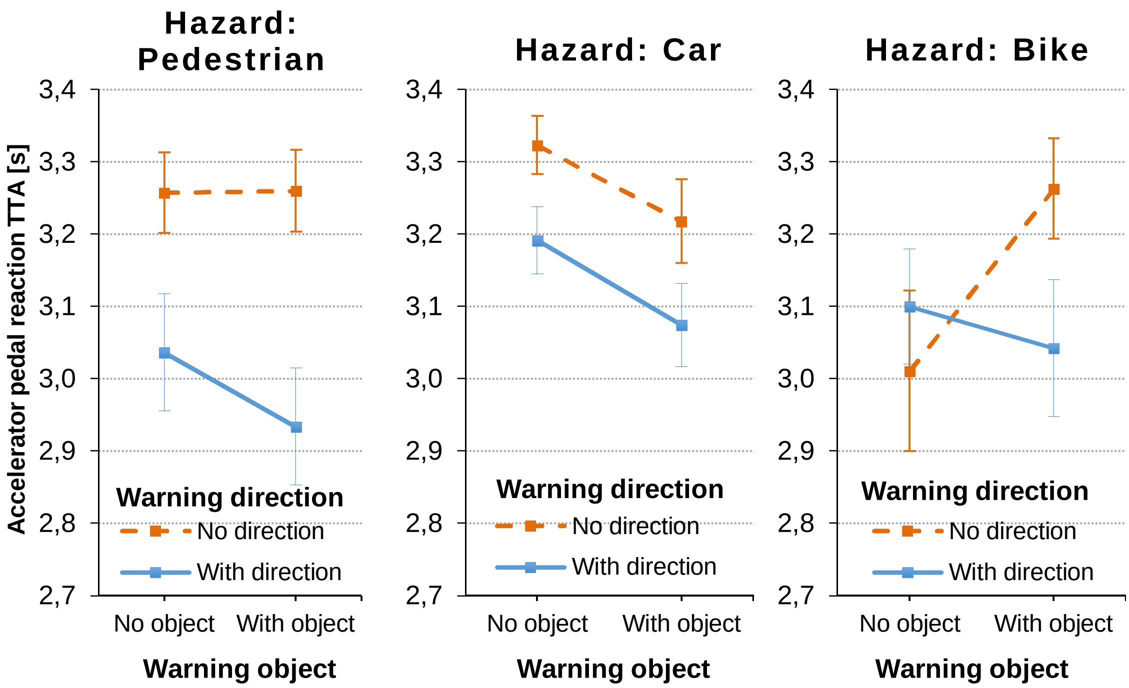

Figure 4.14: Interaction between “Warning direction” and “Warning object” on the accelerator pedal reaction TTA of lateral scenarios grouped by “Hazardous object”.

Brake reaction TTA. The main effect of “Warning direction” led to 200 ms smaller brake reaction TTA for warnings with direction compared to warnings without direction. A smaller brake reaction TTA indicates that participants responded at a closer distance to the hazardous object, in other words, participants responded later.

The main effect of “Warning direction” was modified by the interaction “Warning direction” x “Warning object” x “Hazardous object”. Figure 4.15 illustrates this interaction effect. The effects of brake reaction TTA show the same pattern as the effects of the accelerator pedal reaction TTA. The main effect of “Warning direction” was confirmed for hazardous pedestrian, $t(23) = 6.38$, $p < .001$, $d = 1.30$, and hazardous car, $t(23) = 3.51$, $p < .05$, $d = .72$. In hazardous bike scenarios, the warning with direction led also to 278 ms smaller brake reaction TTA than the warning without direction, $t(23) = 3.67$, $p < .01$, $d = .75$, yet, only when combined with warnings with object. For warnings without object in hazardous bike scenarios, warnings with direction and warnings without direction did not differ, $p > .10$.

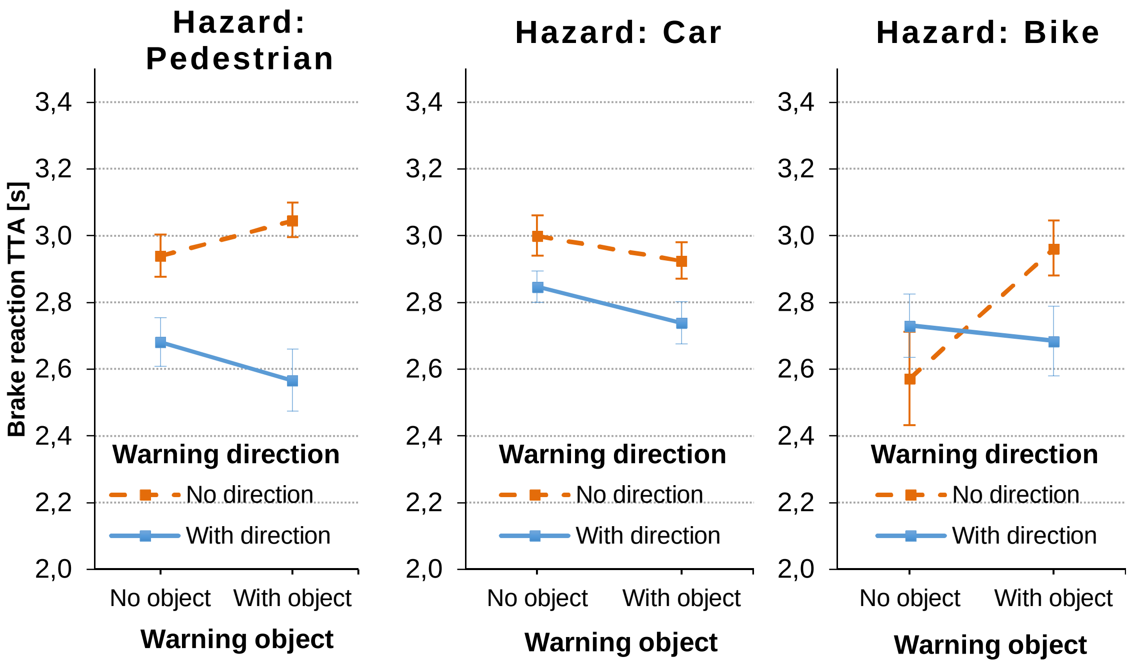

Figure 4.15: Interaction between “Warning direction” and “Warning object” on the brake reaction TTA of lateral scenarios grouped by “Hazardous object”.

Maximum brake pedal position. The main effect of “Warning direction” led to 4% greater maximum brake pedal position for warnings with direction compared to warnings without direction.

The main effect of “Warning direction” was modified by the interaction “Warning direction” x “Warning object” x “Hazardous object”. Figure 4.16 illustrates this interaction effect. The main effect of “Warning direction” was confirmed for hazardous cars only, $t(23) = 3.62$, $p < .05$, $d = .72$. In hazardous pedestrian scenarios, the warning with direction led to 6% greater maximum brake pedal than the warning without direction, $t(23) = 2.64$, $p < .05$, $d = .54$, when combined with warnings with object. For warnings without object in hazardous pedestrian scenarios, warnings with direction and warnings without direction did not differ, $p > .10$. For the hazardous bike scenarios, “Warning direction” had no significant effect on maximum brake pedal position, all p’s > .10.

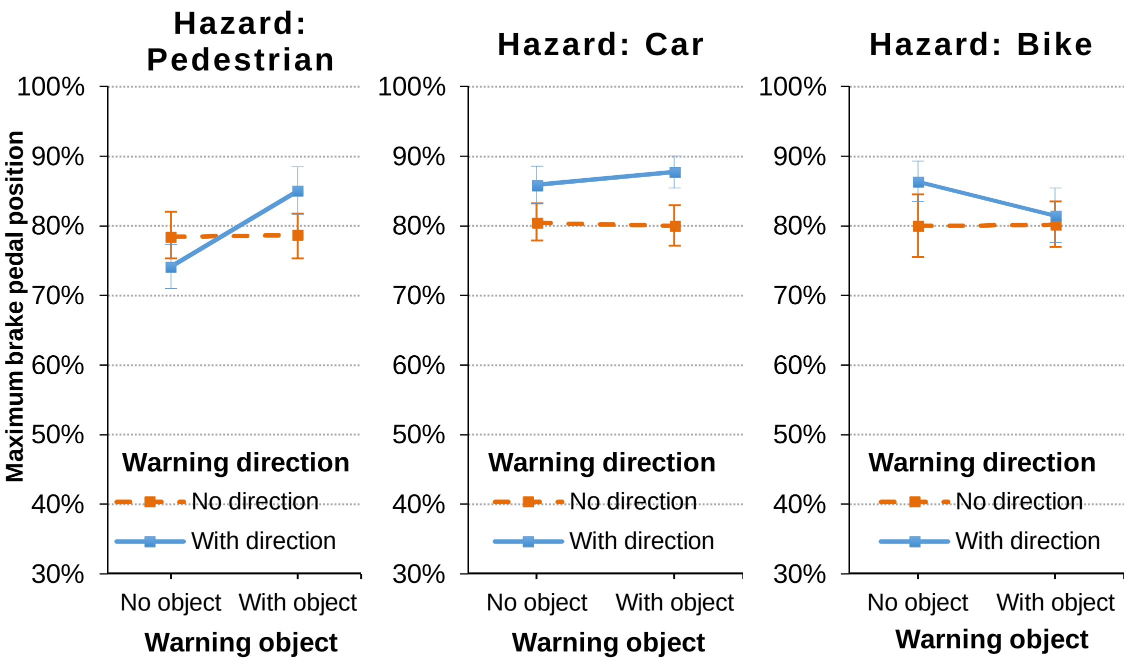

Figure 4.16: Interaction between "Warning direction" and "Warning object" on the maximum brake pedal position of lateral scenarios grouped by "Hazardous object".

Minimum TTA. The main effect of "Warning direction" led to 154 ms smaller minimum TTA for warnings with direction compared to warnings without direction. The smaller minimum TTA indicates that participants stopped their car at a closer distance to the hazard. The main effect of "Warning object" led to 125 ms greater minimum TTA for warnings with object compared to warnings without object. The greater minimum TTA indicates that participants stopped at a greater distance to hazard.

The main effect of "Warning direction" and "Warning object" was modified by the interaction "Warning direction" x "Warning object" x "Hazardous object". Figure 4.18 illustrates this interaction effect. The main effect of "Warning direction" was confirmed for hazardous pedestrian, $t(23) = 2.34$, $p < .05$, $d = .48$, and hazardous car, $t(23) = 4.01$, $p < .05$, $d = .82$. The main effect of "Warning object" was confirmed for hazardous pedestrians. For the hazardous car the "Warning object" showed a reversed effect in comparison to the main effect of "Warning object", Warnings with object led to 149 ms smaller minimum TTA than warnings without object, $t(23) = 2.85$, $p < .01$, $d = .58$.

For warnings without object in hazardous bike scenarios, warnings with direction led to 565 ms greater minimum TTA than warnings without direction, $t(23) = 4.20$, $p < .001$, $d = .86$. In contrast, for warnings with object in hazardous bike scenarios, the warning with direction led to 439 ms smaller minimum TTA than the warning without direction, $t(23) = 4.85$, $p < .001$, $d = .99$.

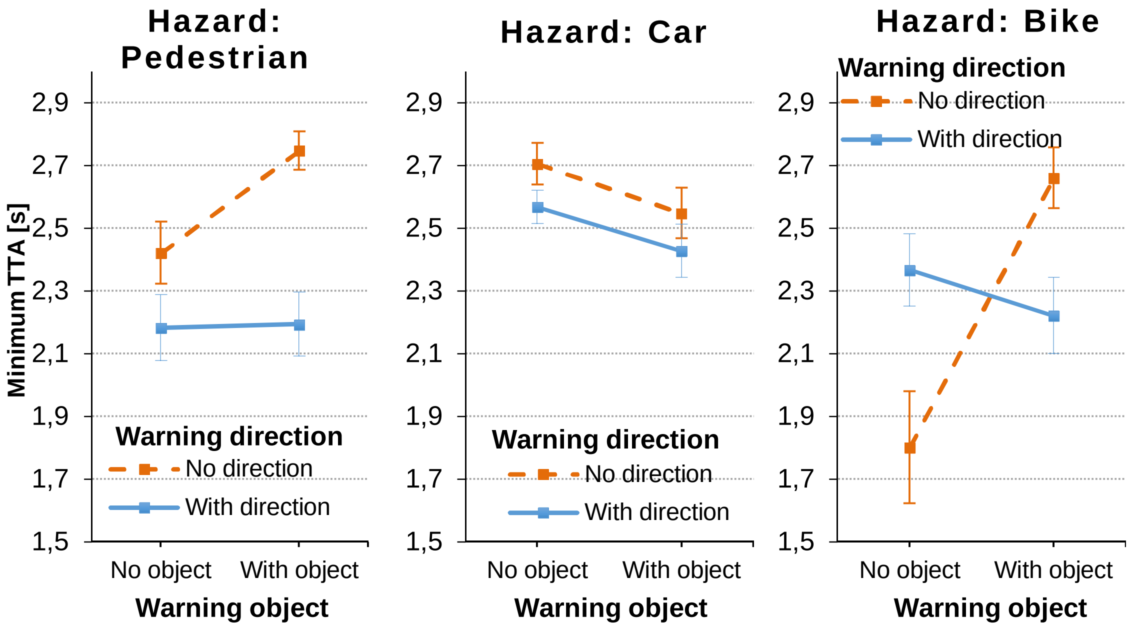

Figure 4.17: Interaction between “Warning direction” and “Warning object” on the minimum TTA of lateral scenarios grouped by “Hazardous object”.

HMI fixation and HMI fixation duration. As Figure 4.19 shows, no differences were found between each warning scheme for the time to HMI fixation and HMI fixation duration in lateral scenarios. All *t*-tests comparing the warning schemes showed a $p > .10$.

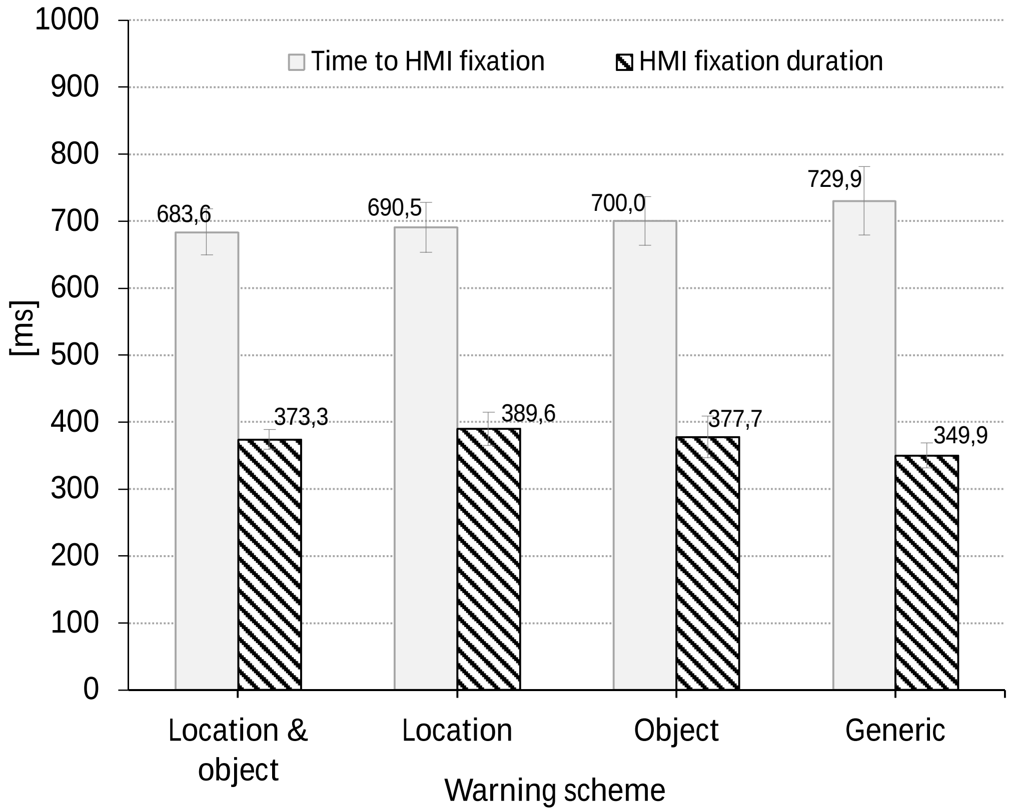

Figure 33: Time to HMI fixation and HMI fixation duration for each warning scheme in lateral scenarios.

Number of collisions. Table 4.3 shows the number of collisions in lateral scenarios. Because collisions occurred rarely, they were only described. For the generic warning scheme (no direction, no object) in bike scenarios, 6 to 8 more collisions occurred compared to other warning schemes in bike scenarios.

Table 4.3: Number of collisions in lateral scenarios

	Number of collisions			
Warning scheme	Pedestrian	Car	Bike	N
Location and object	1	0	2	3
Location	4	0	2	6
Object	0	0	0	0
Generic	1	2	8	11

4.3.1.2 Frontal Scenarios

The factor “Warning direction” showed a main effect on the time to hazard fixation and a marginal effect on the accelerator pedal reaction TTC, see Table 4.1. “Warning object” only led to a main effect on time to hazard fixation. For “Hazardous object” all dependent variables showed a main effect, except of maximum brake pedal position.

The interaction “Warning direction” x “Warning object” and the interaction “Warning direction” x “Hazardous object” were significant for time to hazard fixation and accelerator pedal reaction TTC, see Table 4.2. Furthermore, “Warning object” x “Hazardous object” as well as the triple interaction “Warning direction” x “Warning object” x “Hazardous object” showed an effect on time to hazard fixation and maximum brake pedal position. In the following section the main effects and interaction effects are described for each dependent variable separately.

Table 4.4: Main effects on behavioral variables of frontal warning scenarios

Dependent variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Hazardous object (car, bike)
Time to hazard fixation	$F(1,23) = 43.61$, $\mathbf{p < .001}$**, $\eta_p^2 = .66$	$F(1,23) = 7.57$, $\mathbf{p < .05}$*, $\eta_p^2 = .25$	$F(1,23) = 42.97$, $\mathbf{p < .001}$**, $\eta_p^2 = .65$
Accelerator pedal reaction TTC	$F(1,23) = 3.90$, $p = .06$, $\eta_p^2 = .66$	$F(1,23) = .071$, $p = .79$, $\eta_p^2 = .01$	$F(1,23) = 103.84$, $\mathbf{p < .001}$**, $\eta_p^2 = .82$
Brake reaction TTC	$F(1,23) = 1.80$, $p = .19$, $\eta_p^2 = .07$	$F(1,23) = 1.10$, $p = .31$, $\eta_p^2 = .05$	$F(1,23) = 89.85$, $\mathbf{p < .001}$**, $\eta_p^2 = .80$
Maximum brake pedal position	$F(1,23) = .14$, $p = .72$, $\eta_p^2 = .01$	$F(1,23) = .38$, $p = .55$, $\eta_p^2 = .02$	$F(1,23) = 1.47$, $p = .24$, $\eta_p^2 = .06$
Minimum TTC	$F(1,23) = .56$, $p = .46$, $\eta_p^2 = .02$	$F(1,23) = 3.80$, $p = .06$, $\eta_p^2 = .14$	$F(1,23) = 94.30$, $\mathbf{p < .001}$**, $\eta_p^2 = .80$

Table 4.5: Interaction effects on behavioral variables of frontal warning scenarios

Dependent variable	Warning direction x Warning object	Warning direction x Hazardous object	Warning object x Hazardous object	Warning direction x Warning object x Hazardous object
Time to hazard fixation	$F(1,23) = 14.33$, $\boldsymbol{p < .001}$**, $\eta_p^2 = .38$	$F(1,23) = 20.31$, $\boldsymbol{p < .001}$**, $\eta_p^2 = .47$	$F(1,23) = 12.65$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .36$	$F(1,23) = 6.30$, $\boldsymbol{p < .05}$*, $\eta_p^2 = .22$
Accelerator pedal reaction TTC	$F(1,23) = .21$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .21$	$F(1,23) = 4.87$, $\boldsymbol{p < .05}$**, $\eta_p^2 = .18$	$F(1,23) = .09$, $p = .765$, $\eta_p^2 = .01$	$F(1,23) = .10$, $p = .754$, $\eta_p^2 = .01$
Brake reaction TTC	$F(1,23) = .16$, $p = .69$, $\eta_p^2 = .01$	$F(1,23) = .19$, $p = .18$, $\eta_p^2 = .08$	$F(1,23) = .69$, $p = .416$, $\eta_p^2 = .03$	$F(1,23) = .39$, $p = .54$, $\eta_p^2 = .02$
Maximum brake pedal position	$F(1,23) = 2.59$, $p = .12$, $\eta_p^2 = .10$	$F(1,23) = 1.65$, $p = .21$, $\eta_p^2 = .07$	$F(1,23) = 4.32$, $\boldsymbol{p < .05}$*, $\eta_p^2 = .16$	$F(1,23) = 9.85$, $\boldsymbol{p < .01}$**, $\eta_p^2 = .30$
Minimum TTC	$F(1,23) = 2.11$, $p = .16$, $\eta_p^2 = .08$	$F(1,23) = 2.19$, $p = .15$, $\eta_p^2 = .09$	$F(1,23) = 2.81$, $p = .11$, $\eta_p^2 = .11$	$F(1,23) = 1.11$, $p = .30$, $\eta_p^2 = .05$

Time to hazard fixation. The main effect of "Warning direction" led to 315 ms faster hazardous object fixation for warnings with direction compared to warnings without direction. The main effect of "Warning object" led to 120 ms faster hazardous object fixation for warnings with object compared to warnings without object.

The main effects of "Warning direction" and of "Warning object" were modified by the interaction "Warning direction" x "Warning object" x "Hazardous object". Figure 4.18 illustrates this interaction effect. For warnings without object, the warning with direction led to faster hazardous object fixation than for warnings without direction, for hazardous car, 908 ms, $t(23) = 5.82$, $p < .001$, $d = 1.19$ and for hazardous bike, 216 ms, $t(23) = 5.32$, $p < .001$, $d = 1.09$. In contrast, for warnings with object, the warning with direction and the warning without direction did not differ, $p > .10$. Furthermore, for hazardous cars, warning with object led to faster time to hazard fixation than warning without object, $t(23) = 5.82$, $p < .001$, $d = 1.19$, yet, only when combined with warnings without direction.

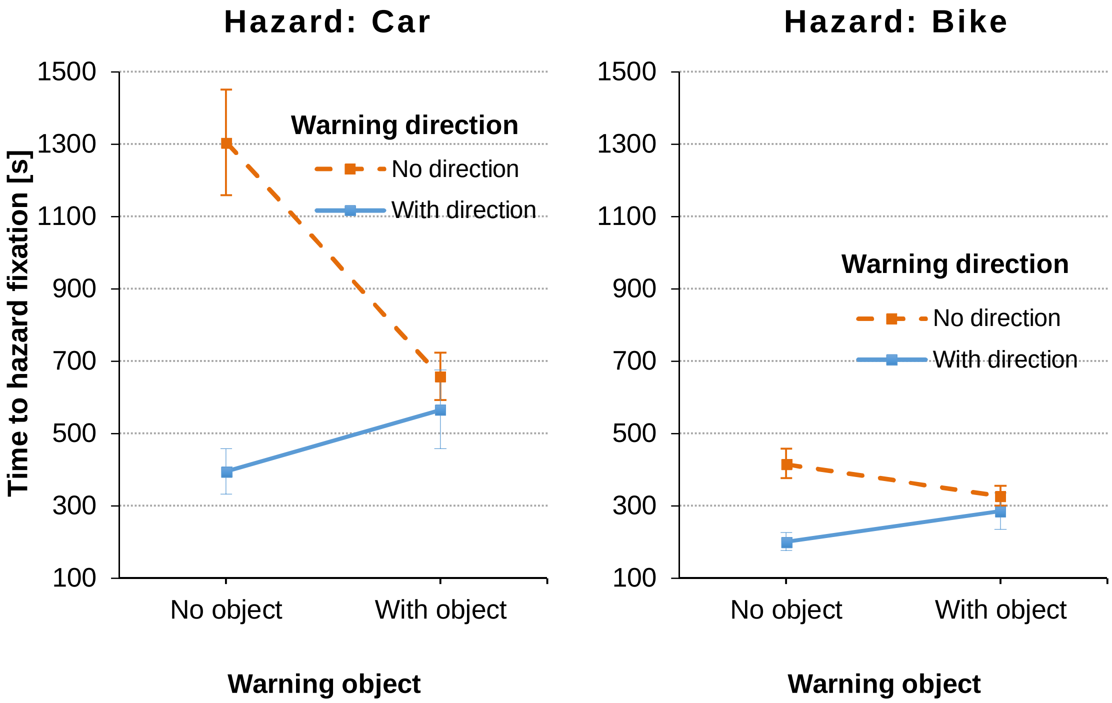

Figure 4.18: Interaction between “Warning direction” and “Warning object” on the time to hazard fixation of frontal scenarios grouped by “Hazardous object”.

Accelerator pedal reaction TTC. The marginal main effect of “Warning direction” led to 91 ms smaller accelerator pedal reaction TTC for warnings with direction compared to warnings without direction. A smaller accelerator pedal reaction TTC indicates that participants responded at a closer distance to the hazardous object, in other words, participants responded later.

In hazardous car scenarios, warnings with direction led to smaller accelerator pedal reaction TTC than warnings without direction, see Figure 4.19. This effect, however, was statistically significant only for warnings with object, $t(23) = 2.26$, $p < .05$, $d = .46$, and failed the significance level ($p = .13$) for warning without object. “Warning object” and “Warning direction” had no effect on accelerator pedal reaction TTC for hazardous bike scenarios, $p > .10$.

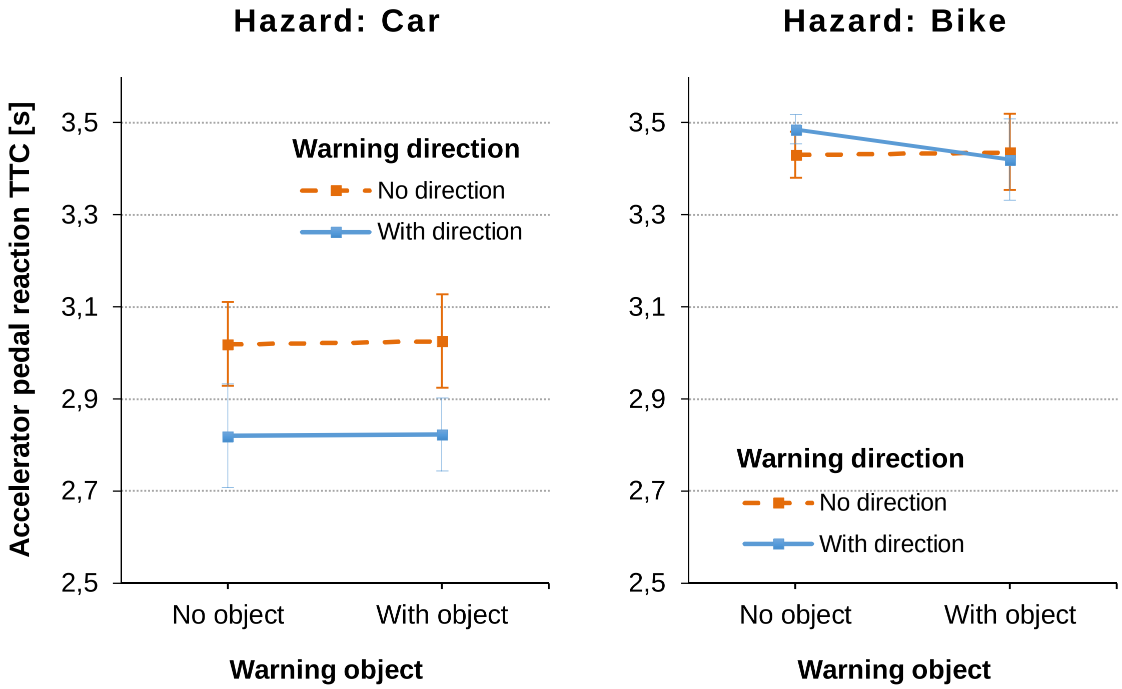

Figure 4.19: Interaction between “Warning direction” and “Warning object” on the accelerator pedal reaction TTC of frontal scenarios grouped by “Hazardous object”.

Brake reaction TTC. “Warning direction” and “Warning object” showed no main effect or interaction effect on the brake reaction TTC, see Figure 4.20.

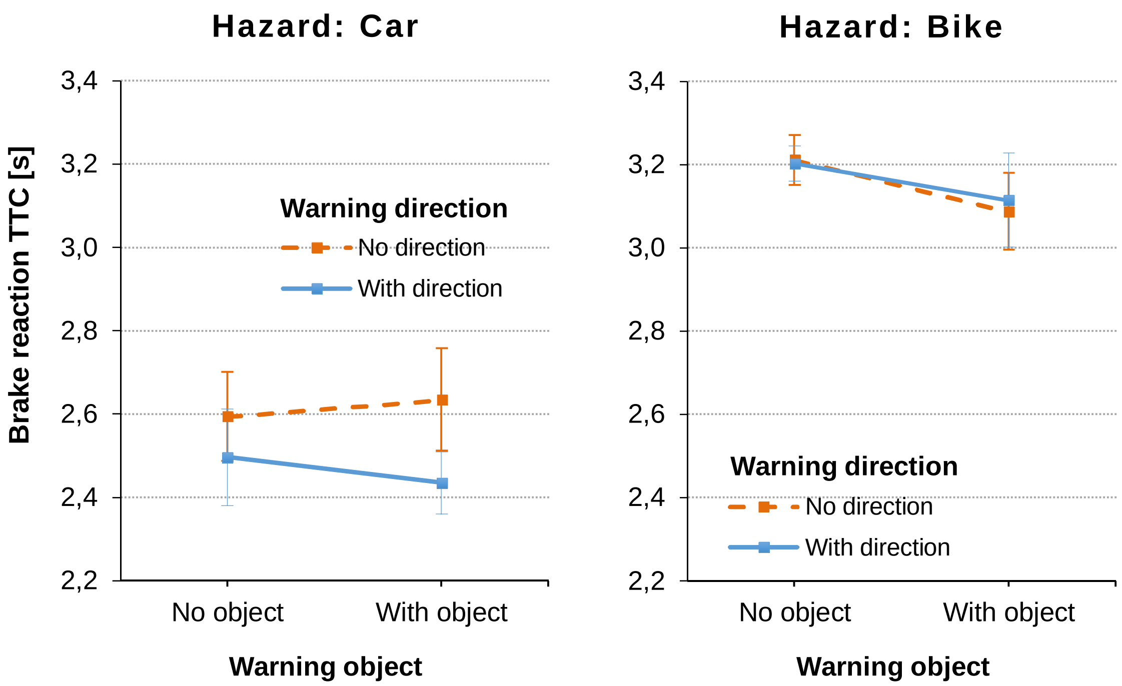

Figure 4.20: Interaction between “Warning direction” and “Warning object” on the brake reaction TTC of frontal scenarios grouped by “Hazardous object”.

Maximum brake pedal position. "Warning direction" and "Warning object" showed no main effect on the maximum brake pedal position, but the triple interaction "Warning direction" x "Warning object" x "Hazardous object" was significant regarding the maximum brake pedal position. Figure 4.21 illustrates this interaction effect. Only for warnings with object in hazardous bike scenarios, the warning with direction led to 7% higher maximum brake pedal position than for warnings without direction, $t(23) = 3.21$, $p < .05$, $d = .65$. All other comparisons for "Warning direction" and "Warning object" did not reach significance, $p > .05$.

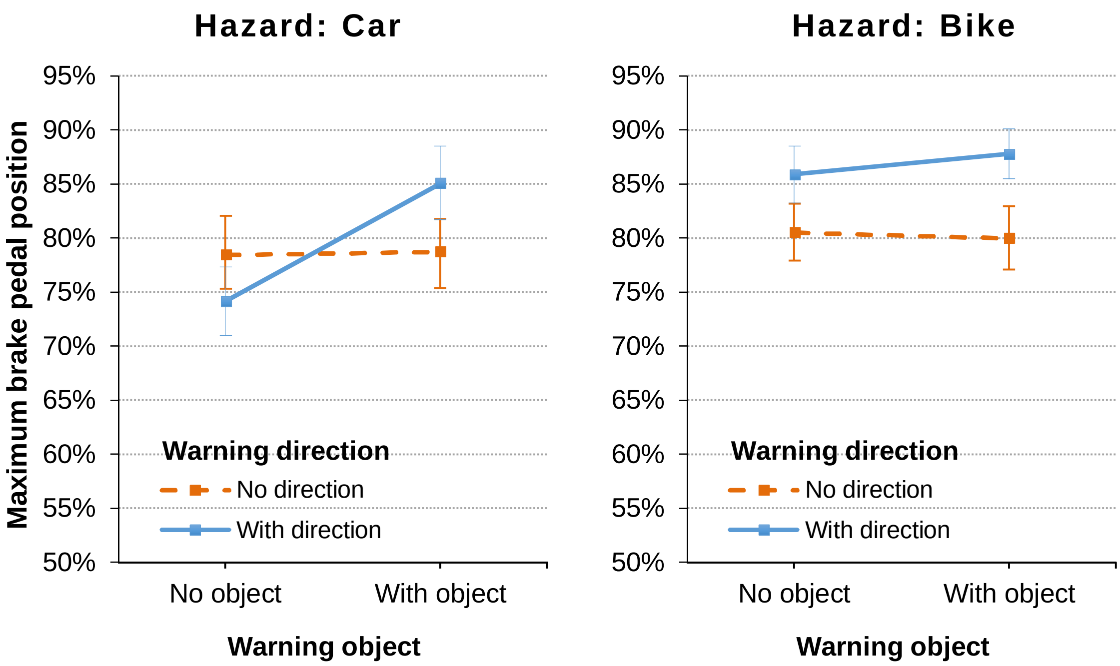

Figure 4.21: Interaction between "Warning direction" and "Warning object" on the maximum brake pedal position of frontal scenarios grouped by "Hazardous object".

Minimum TTC. "Warning direction" and "Warning object" showed no main effect or interaction effect on the minimum TTC, see Figure 4.22.

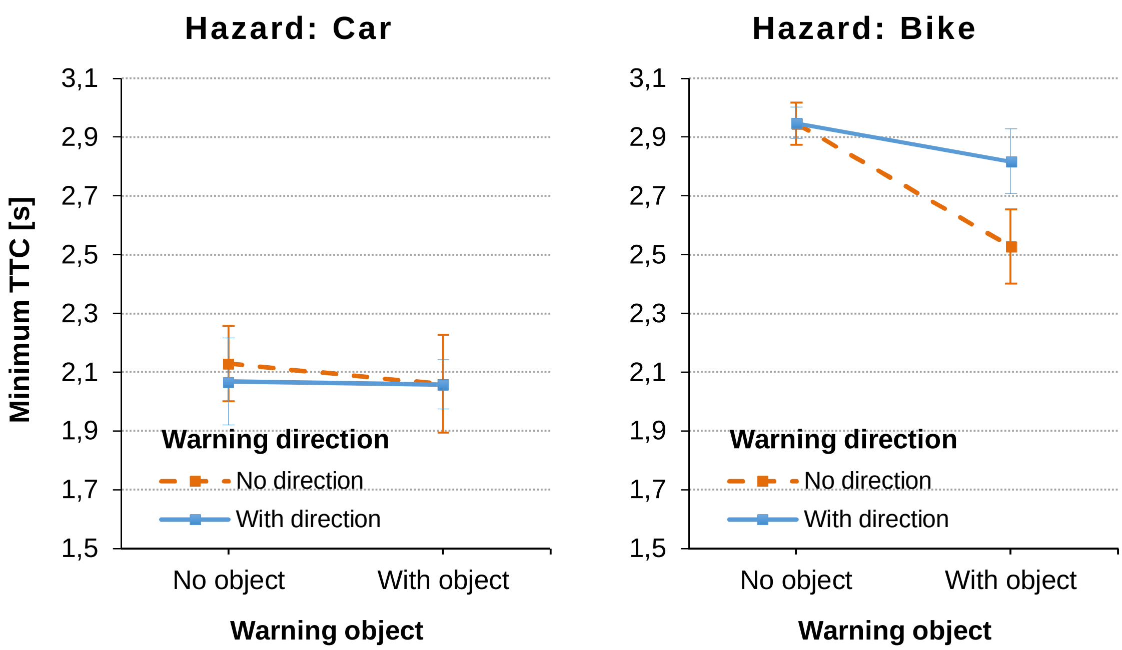

Figure 4.22: Interaction between “Warning direction” and “Warning object” on the minimum TTC of frontal scenarios grouped by “Hazardous object”.

HMI fixation and HMI fixation duration. As Figure 4.23 shows, no differences were found for the time to HMI fixation and HMI fixation duration between each warning scheme for frontal scenarios. All *t*-tests comparing the warning schemes showed a $p > .10$.

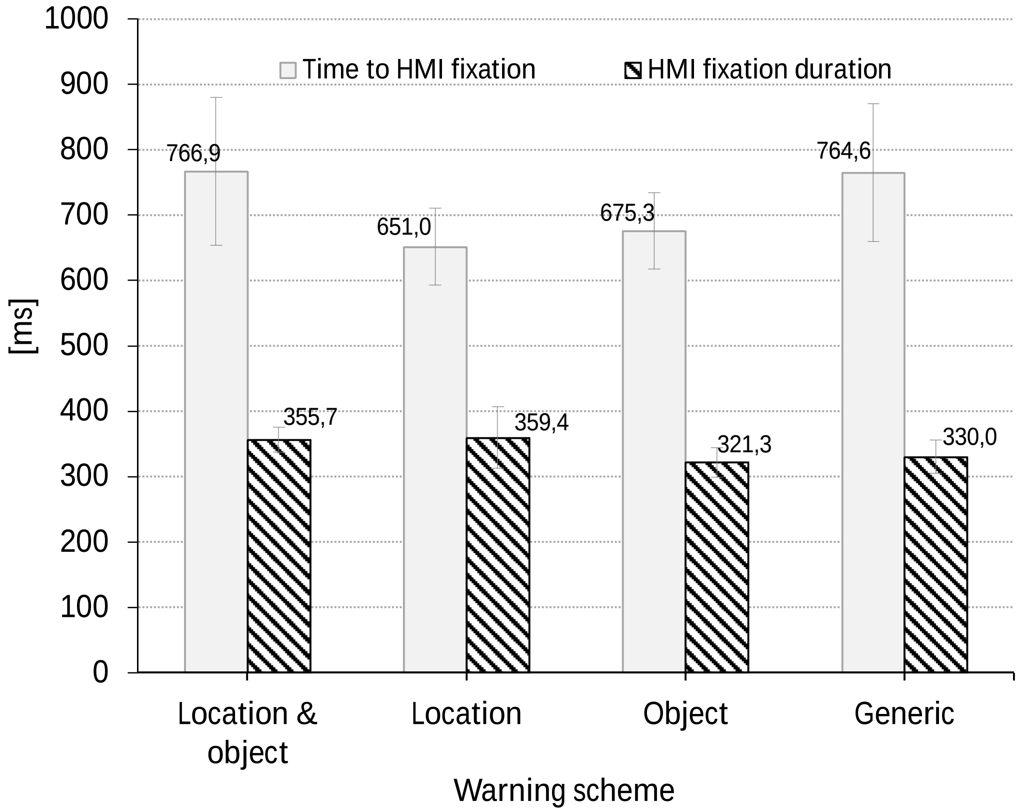

Figure 4.23: Time to HMI fixation and HMI fixation duration for each warning scheme in frontal warning scenarios.

Number of collisions. Table 4.6 shows the number of collisions in frontal scenarios. Because collisions occurred rarely, they were only described. In hazardous car scenarios, depending on the warning scheme, one to three collisions occurred. No collisions occurred in frontal bike scenarios.

Table 4.6: Number of collisions in frontal scenarios.

	Number of collisions		
Warning scheme	Car	Bike	N
Location and object	1	0	1
Location	2	0	2
Object	3	0	3
Generic	1	0	1

4.3.1.3 Unnecessary Warnings

Number of brake reactions. As Figure 4.24 shows, the majority of braking reactions in unnecessary warning scenarios occurred for the warning scheme location and object, followed by the warning schemes: generic, object, and location.

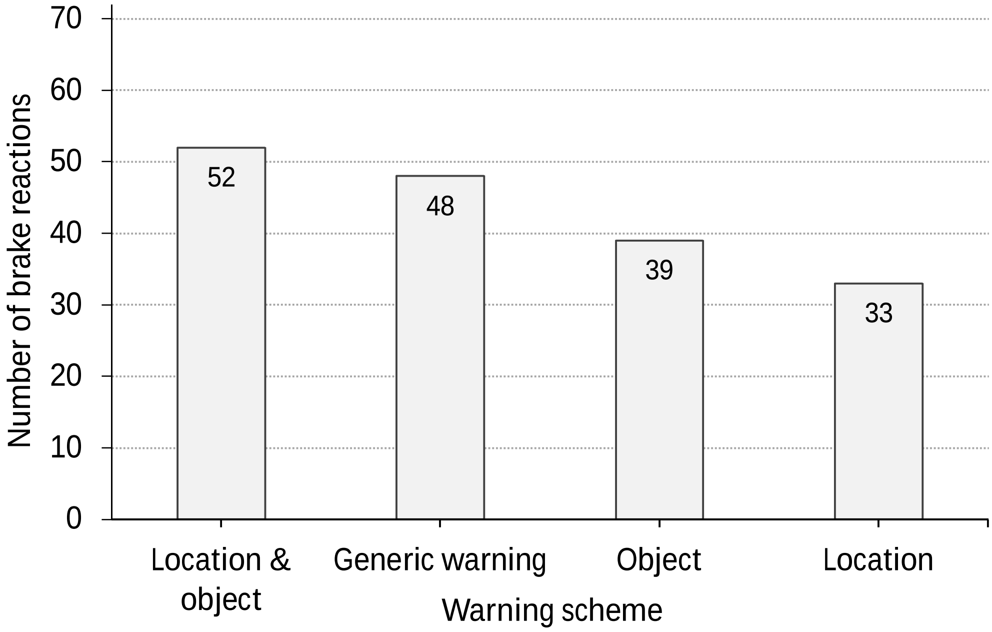

Figure 4.24: Number of brake reactions for each warning scheme regarding unnecessary warning scenarios, sorted ascending. Overall there were 72 possible brake reactions for each warning scheme.

HMI fixation and HMI fixation duration. As Figure 4.25 shows, no differences were found for the time to HMI fixation and HMI fixation duration between each warning scheme for unnecessary warning scenarios. All *t*-tests comparing the warning schemes showed a $p > .10$. This is the same finding as for lateral and frontal scenarios.

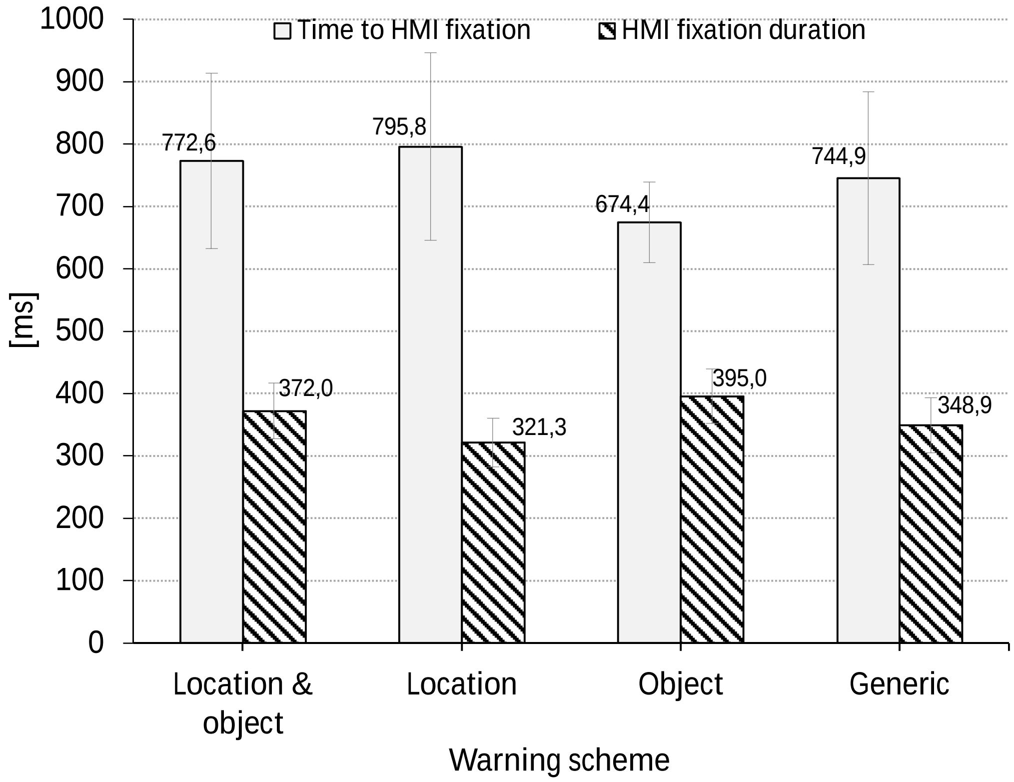

Figure 4.25: Time to HMI fixation and HMI fixation duration for each warning scheme in unnecessary warning scenarios.

4.3.2 Direct Warning Ratings in Scenarios

4.3.2.1 Usefulness of Warning for Lateral Scenarios

Regarding lateral scenarios, the factor "Warning direction", "Warning object" and "Hazardous object" showed a main effect, see Table 4.7. On average, warnings with direction were rated 1.3 points more useful than warnings without direction. On average warnings with object were rated .4 points more useful than warnings without object. The usefulness of warning ratings differed for the hazardous objects.

The interaction "Warning object" x "Hazardous object" as well as the triple interaction "Warning direction" x "Warning object" x "Hazardous object" were significant, see Table 4.8. Figure 4.26 illustrates these interaction effects grouped by "Hazardous object". The further analysis of the interactions confirmed the mean effect of "Warning direction", for hazardous pedestrian, $t(23) = 6.99$, $p < .01$, $d = .143$, for hazardous car, $t(23) = 4.80$, $p < .001$, $d = .98$, and for hazardous bike, $t(23) = 3.45$, $p < .05$, $d = .70$.

"Warning object" showed an effect for the hazardous pedestrians only. For the hazardous pedestrians, warnings with object were rated .9 points more useful than warnings without object, $t(23) = -4.77$, $p < .001$, $d = .97$. "Warning object" had no effect for hazardous cars and hazardous bikes, both $p > .10$.

Table 4.7: Main effects on the usefulness of warning of lateral scenarios

Dependent variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Hazardous object (ped., car, bike)
Usefulness of warning	$F(1,23) = 39.69$, **$p < .001$****, $\eta_p^2 = .63$	$F(1,23) = 12.91$, **$p < .05$****, $\eta_p^2 = .36$	$F(2,46) = 8.36$, **$p < .001$****, $\eta_p^2 = .27$

Table 4.8: Interaction effects on the usefulness of warning of lateral scenarios

Dependent variable	Warning direction x Warning object	Warning direction x Hazardous object	Warning object x Hazardous object	Warning direction x Warning object x Hazardous object
Usefulness of warning	$F(1,23) = 4.21$, $p = .05$, $\eta_p^2 = .15$	$F(2,46) = .93$, $p = .93$, $\eta_p^2 < .01$	$F(2,46) = 3.56$, **$p < .05$***, $\eta_p^2 = .13$	$F(2,46) = 4.15$, **$p < .05$***, $\eta_p^2 = .15$

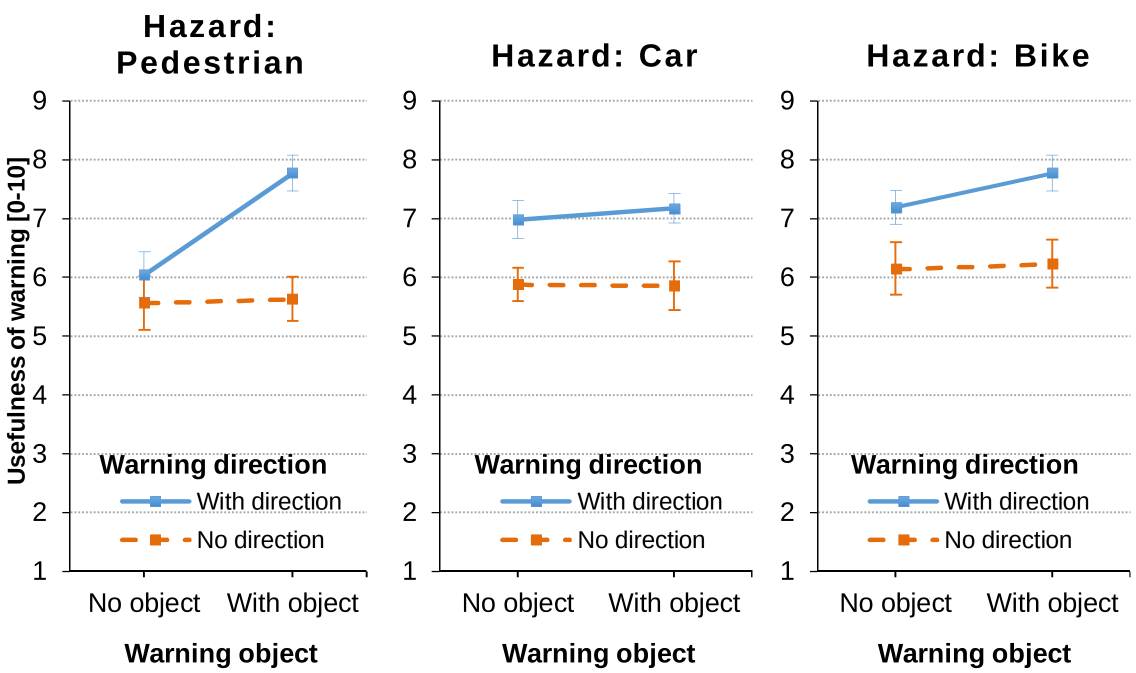

Figure 4.26: Interaction between "Warning direction" and "Warning object" on the usefulness of warnings of lateral scenarios grouped by "Hazardous object".

4.3.2.2 Usefulness of Warning for Frontal Scenarios

For frontal scenarios the factor "Warning object" and "Hazardous object" showed a main effect, see Table 4.9. On average, warnings with object were rated .8 points more useful than warnings without object.

The two-way interaction between "Warning object" x "Hazardous object" was also significant, see Table 4.10. Figure 4.27 illustrates the interaction effect grouped by "Hazardous object". The further analysis of the interactions only confirmed the main effect of "Warning object" for hazardous bikes, $t(23) = 3.46$, $p < .05$, $d = .71$, whereas for hazardous cars warnings with object were rated marginally more useful than warnings without objects, $t(23) = 1.96$, $p = .06$, $d = .40$.

Table 4.9: Main effects on the usefulness of warning of frontal scenarios

Dependent variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Hazardous object (ped., car, bike)
Usefulness of warning	$F(1,23) = 1.95$, $p = .18$, $\eta_p^2 = .08$	$F(1,23) = 15.96$, **$p < .001$****, $\eta_p^2 = .41$	$F(1,23) = 8.30$, **$p < .01$****, $\eta_p^2 = .27$

Table 4.10: Interaction effects on the usefulness of warning of frontal scenarios

Dependent variable	Warning direction x Warning object	Warning direction x Hazardous object	Warning object x Hazardous object	Warning direction x Warning object x Hazardous object
Usefulness of warning	$F(1,23) = 1.62$, $p = .22$, $\eta_p^2 = .07$	$F(2,46) = 1.20$, $p = .28$, $\eta_p^2 = .05$	$F(2,46) = 4.46$, **$p < .05$***, $\eta_p^2 = .16$	$F(2,46) = .64$, $p = .43$, $\eta_p^2 = .03$

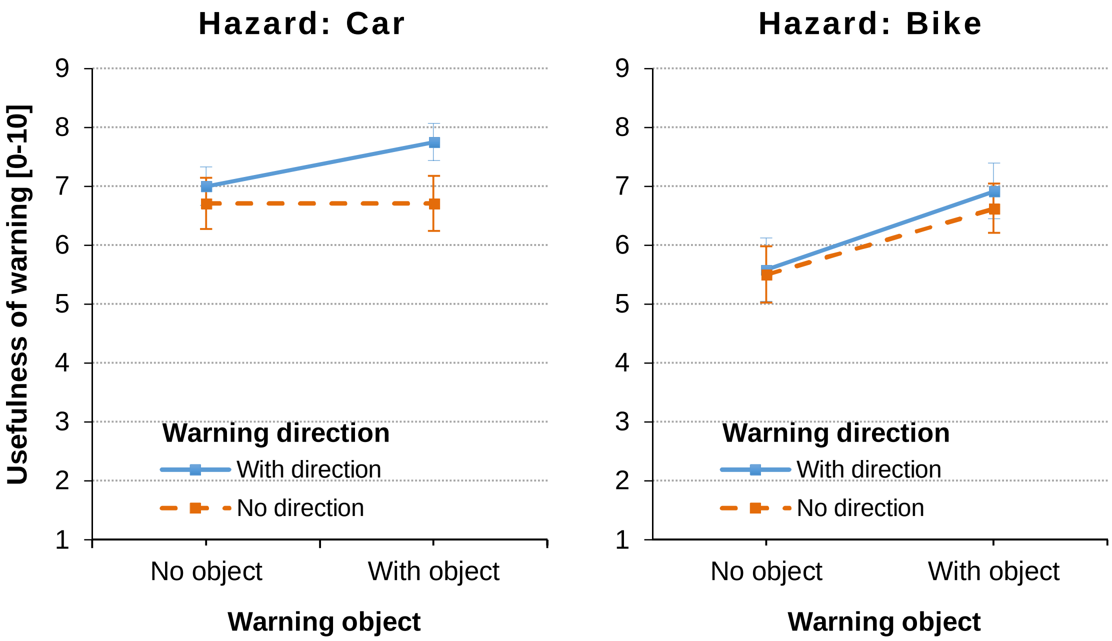

Figure 4.27: Interaction between "Warning direction" and "Warning object" on the usefulness of warnings of frontal scenarios grouped by "Hazardous object".

4.3.2.3 Usefulness of Warning for Unnecessary Warning Scenarios

For unnecessary warnings the factor Warning object showed a main effect, see Table 4.11. On average, warnings with object were rated .7 points more useful than warnings without object.

The main effect of "Warning object" was modified by the interaction "Warning direction" x "Warning object". Figure 4.28 illustrates this interaction effect. For warnings without direction, the warning with object led to 2.4 points higher usefulness ratings than the warning without object, $t(23) = 8.45$, $p < .001$, $d = 1.7$. In contrast, for warnings with direction the warning with object led to 1 point lower usefulness ratings than warning without object, $t(23) = 3.31$, $p < .05$, $d = .7$.

Table 4.11: Effects on the usefulness of warning of unnecessary warning scenarios

Depended variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Warning direction x Warning object
Usefulness of warning	$F(1,23) = .69$, $p = .41$, $\eta_p^2 = .03$	$F(1,23) = 9.13$, $\mathbf{p < .01^{**}}$, $\eta_p^2 = .28$	$F(1,23) = 86.34$, $\mathbf{p < .001^{**}}$, $\eta_p^2 = .79$

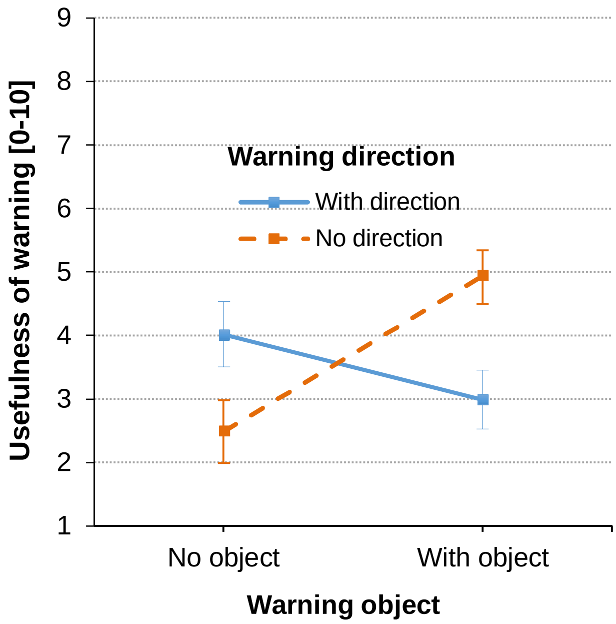

Figure 4.28: Interaction between “Warning direction” and “Warning object” on the usefulness of warnings of unnecessary warning scenarios.

4.3.3 Warning Ratings after Driving

The factor “Warning direction” and “Hazardous object” showed a main effect on the post ratings of usefulness of warning, which were assessed after driving, see Table 4.6. On average, warnings with direction were rated .5 points more useful than warnings without direction.

The interaction between “Warning object” x Hazard was also significant, see Table 4.12. Figure 4.29 illustrates this interaction effect grouped by “Hazardous object”. The main effect of “Warning direction” could only be confirmed for the hazardous pedestrian, $t(23) = 2.82$, $p < .05$, $d = .58$. “Warning direction” had no effect on post ratings of usefulness of warning for hazardous car and hazardous bike, both $p > .10$. The post ratings of warning usefulness were assessed after each driving block and indicate less differences for the warning schemes than the direct ratings of warning usefulness for the warning schemes, section 4.3.2 shows the direct ratings.

Table 4.12: Main effects on post ratings of usefulness of warning

Dependent variable	Warning direction (no direction, with direction)	Warning object (no object, with object)	Hazardous object (ped., car, bike)
Usefulness of warning	$F(1,23) = 6.43$, **$p < .05$***, $\eta_p^2 = .22$	$F(1,23) = 1.84$, $p = .19$, $\eta_p^2 = .07$	$F(1,23) = 3.23$, **$p < .05$***, $\eta_p^2 = .12$

Table 4.13: Interaction effects on post ratings of usefulness of warning

Dependent variable	Warning direction x Warning object	Warning direction x Hazardous object	Warning object x Hazardous object	Warning direction x Warning object x Hazardous object
Usefulness of warning	$F(1,23) = .17$, $p = .69$, $\eta_p^2 = .01$	$F(2,46) = 1.20$, $p = .31$, $\eta_p^2 = .05$	$F(2,46) = 7.08$, **$p < .01$****, $\eta_p^2 = .24$	$F(2,46) = .04$, $p = .96$, $\eta_p^2 = .01$

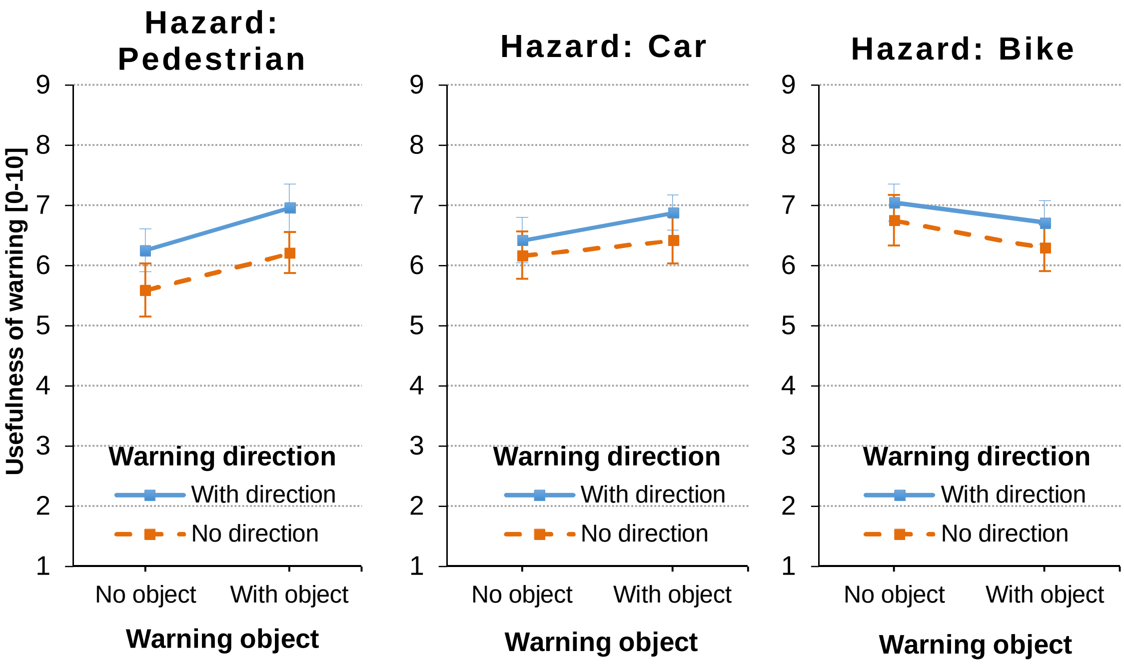

Figure 4.29: Interaction between “Warning direction” and “Warning object” on the usefulness of warnings (post ratings) grouped by “Hazardous object”.

4.3.4 Subjective Data

The following section focuses on subjective scales to evaluate the warning schemes and comments made in connection with open questions and interviews. The trust in system for the location and object warning scheme was rated .9 points higher than for the object warning scheme and 1 point higher than for the generic warning scheme. All other t-tests comparing the trust in system for the warning schemes showed a non-significant $p > .10$.

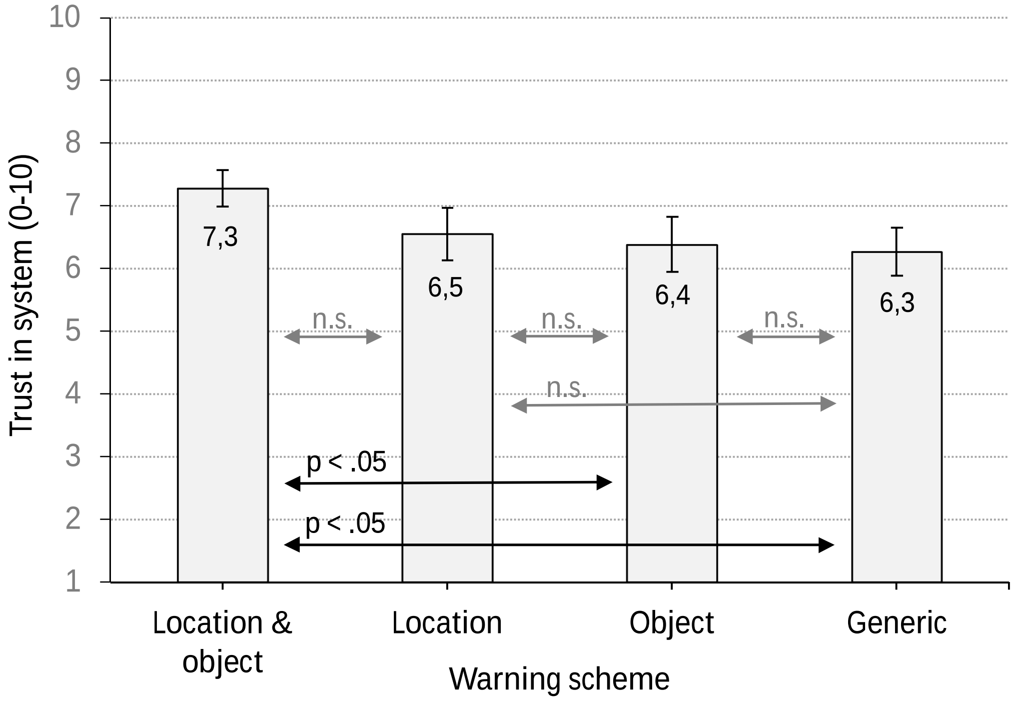

Figure 4.30: Trust in system for each warning scheme.

On average, participants were willing to pay from 381 € to 493 € for the warning systems. As Figure 4.31 shows, the willingness to pay did not differ for the warning schemes. All t-tests comparing the warning schemes showed a $p > .10$. There is a slight descriptive tendency that participants were willing to pay more for the system with the location and object warning scheme than for the system with the generic warning scheme.

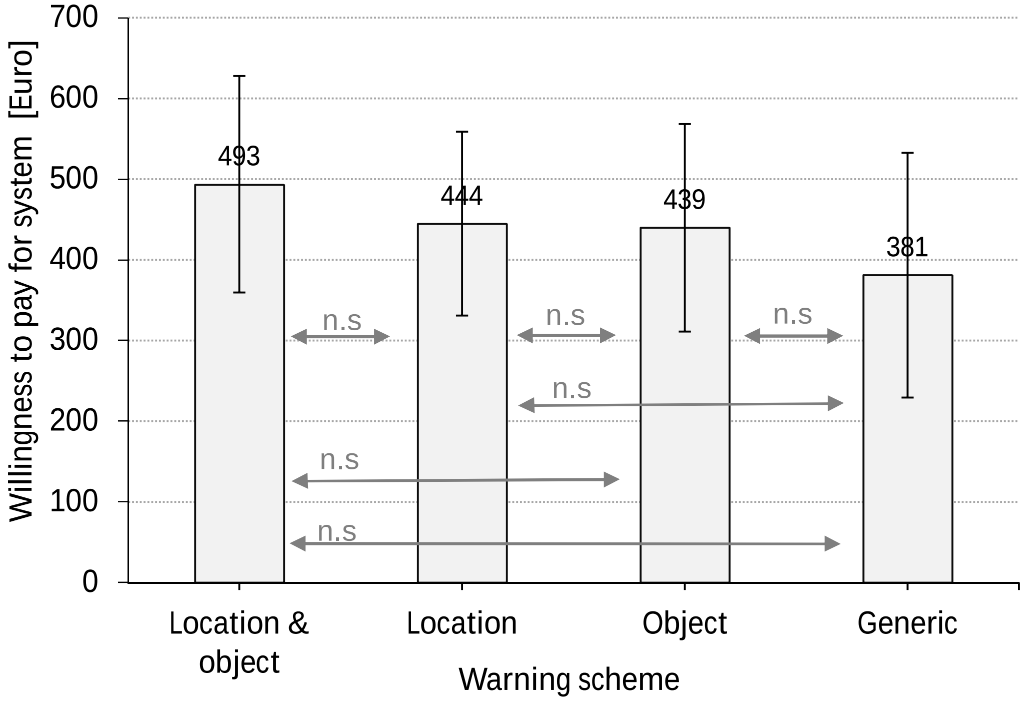

Figure 4.31: Willingness to pay for system for each warning scheme.

As Figure 4.32 illustrates, the preference to use the warning system in the own car did not differ for the warning scheme. All *t*-tests comparing the warning schemes showed a $p > .10$. In general the ratings indicate a tendency to use a system in one's own car because in average all ratings stay over 2.5 points. Furthermore, the generic warning (no direction, no object) is rated descriptively lower than all other assessed warning schemes.

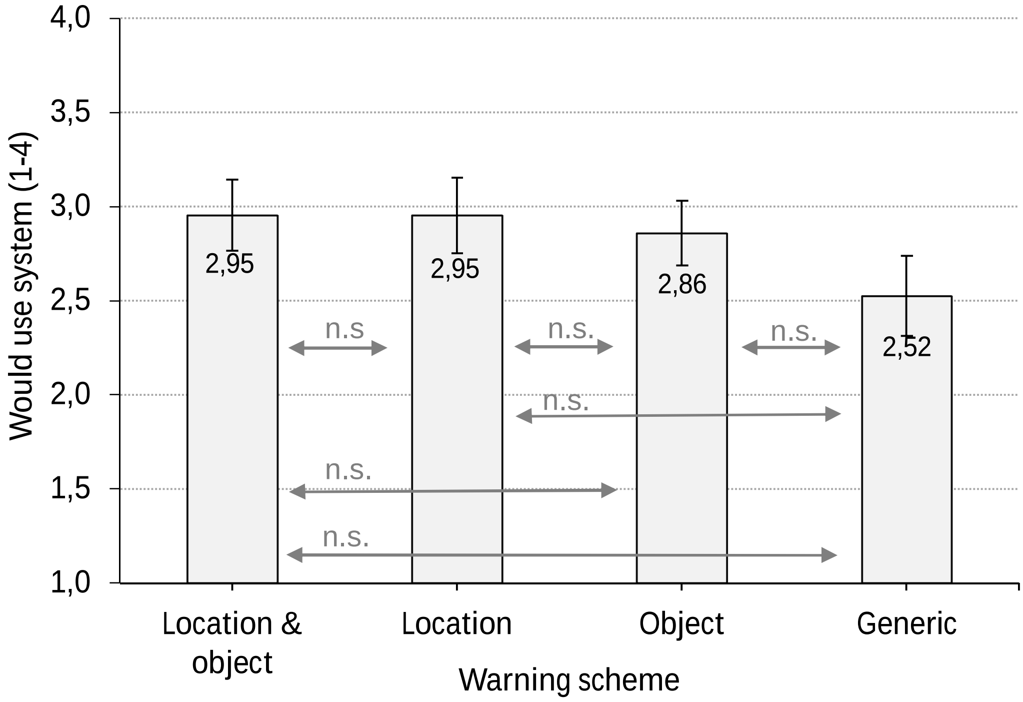

Figure 4.32: Preference to use warning system in own car for each warning scheme.

The following section includes a collection of frequent and important comments made in questionnaires and during interviews (Comments are translated; original comments were in German):

- The direction cue helped me to identify the hazardous object.
- The tone was important because it alerted me. It helped me to look at the visual HMI and thereby to search for the hazard.
- I would prefer a visual warning in the windshield (e.g., head-up display) because it can be dangerous to look down to the cluster if I recognized the warning too late.
- I missed the more specific information like direction and object cues in the driving blocks with the generic warning. I had the specific warning in the first driving block.
- If the warning in unnecessary warning scenarios helped me to identify the possible hazardous object, it was not as bad as if I wasn't able to spot the possible hazard.

4.3.5 Summary

Four ADAS warning schemes were used to examine the effects of “Warning direction” (no direction, with direction) and “Warning object” (no object, with object) in an urban test track, including frontal and lateral hazardous scenarios. Unnecessary warning scenarios were also analyzed. “Warning direction” was implemented by visual and auditory direction cues, the “Warning object” was implemented by visual symbols indicating the type of hazardous object. For each of the four warning schemes, participants drove an individual driving block sequence with a permuted order.

Most effects were found for “Warning direction” in **lateral scenarios**, see Table 4.14. Regarding lateral scenarios, warnings with direction led to faster hazardous object fixation than warnings without direction, yet, only when combined with warning without object. This means, the warning direction cue facilitated the time to hazardous object fixation, yet, only if no warning object cue was included in the visual warning. On the contrary, if a warning object cue was included into the warning related to hazardous pedestrians and hazardous bikes, warnings with direction led to slower hazardous object fixation than warnings without direction.

Table 4.14: Effects of warning with direction for lateral and frontal scenarios of Study 2

Dependent variable	Warning scenarios	
	Lateral	*Frontal*
Time to hazardous object fixation (smaller = faster fixation)	**Ped.** NO**--**, O**+** **Car.** NO**--** **Bike** NO**--**, O**+**	**Car.** NO**--** **Bike** NO**--**
Accelerator pedal reaction TTA (smaller = slower & closer distance to hazard)	**Ped.--** **Car--** **Bike** O**-**	*n.s.*
Brake reaction TTA (smaller = slower & closer distance to hazard)	**Ped.--** **Car-** **Bike** O**--**	*n.s.*
Maximum brake pedal position (higher = more intensive)	**Car+**	**Bike+**
Minimum TTA (smaller = stopped at a closer distance to hazard)	**Ped.-** **Car-** **Bike** NO**++**, O**--**	*n.s.*
Direct warning usefulness ratings (higher = more useful)	**Ped.++** **Car++** **Bike+**	*n.s.*

Note. Effects of warning with direction are shown separately for each hazardous object regarding lateral and frontal scenarios. Ped. = pedestrian. The hazardous objects are followed by **+** and **-**, indicating the effect of a warning with direction compared to warning without direction. The suffix **--** indicates lower value with a p <.001 for warning with direction compared to a warning without direction; **-** indicates lower value with a p < .05; **++** indicates higher value with a p <.001; **+** indicates higher value with a p <.05; n.s. indicates no significant effect with a p >.10. Suffix O = Effect of warning with direction when combined with warning with object. Suffix NO = Effect of warning with direction when combined with warning without object.

Furthermore, for hazardous pedestrians and hazardous cars, warning with direction led to smaller accelerator pedal reaction TTA, smaller brake reaction TTA, slightly higher maximum brake pedal position[20], and smaller minimum TTA, see Table 4.14. This means, participants who were alerted by warning direction cues responded later and stopped at a closer distance to the hazardous objects compared to warnings without direction cues.

For lateral scenarios with hazardous bike, all behavioral variables led to an interaction of "Warning direction" x "Warning object" x "Hazardous object". Warning with direction led to smaller accelerator pedal reaction TTA, smaller brake reaction TTA, and

[20]Only for hazardous car.

smaller minimum TTA, yet, only when combined with warning with object. This means, for warnings with direction, participants responded later and stopped at a closer distance to the hazard than for warnings without direction, yet, only if the warnings did contain an object cue. In contrast, if warnings did not contain an object cue, warnings with direction led to greater minimum TTA compared to warnings without direction. Regarding the warning usefulness in lateral scenarios, warnings with direction led consistently to higher warning usefulness ratings (directly assessed) compared to warnings without direction.

The "Warning object" showed only few effects in lateral scenarios. For hazardous pedestrians, warning with object led to greater minimum TTA and higher warning usefulness ratings than warning without object. The greater minimum TTA indicated that participants stopped at a greater distance to the hazardous pedestrians. Furthermore, for hazardous cars in lateral scenarios, warning with object led to smaller minimum TTA than warnings without object, indicating that participants stopped at a closer distance to the hazardous car.

As suggested by the hypotheses, "Warning direction" and "Warning object" led to few effects for **frontal scenarios**. For hazardous cars and hazardous bikes, warning with direction led to faster time to hazard fixation than warning without direction, yet, only when combined without object cue. Furthermore, only for hazardous cars, warning with object led to faster time to hazard fixation than warning without object, yet, only when combined without direction cue. For hazardous bikes scenarios, warning with direction led to higher maximum brake pedal position than warning without direction.

For **unnecessary warnings**, the number of braking reactions showed no clear difference between the warning schemes. For warning scheme location (with direction, no object) descriptively less brake reactions occurred than for the warning scheme generic (no direction, no object) and the warning scheme location and object (with location, with object). The direct ratings of warning usefulness showed an interaction between "Warning direction" and "Warning object". For unnecessary warnings without direction, the warning with object led to higher usefulness ratings than warning without object. In contrast, for unnecessary warnings with direction, the warning with object led to lower usefulness ratings than warning without object.

In contrast to the directly assessed warning usefulness, **post ratings of warning usefulness** were assessed after driving. Overall, the post ratings of warning usefulness showed considerably less differences for the warning schemes than the direct ratings of warning usefulness for the warning schemes. For hazardous pedestrian scenarios, warnings with direction were rated more useful than warnings without direction. This effect was also present for warning with direction cue and object cue. No further effects were found for the post ratings of warning usefulness.

Subjective scales that evaluated the willingness to pay for the warning system and the preference to use the experienced warning system, did not differ between the warning schemes. On average participants were willing to pay about 450 € for the experienced warning systems and had a light preference to use the experienced warning systems in their own car. For the trust in the system, the warning scheme location and object (with direction, with object) showed higher scores than the warning scheme object (no direction, with object) and the generic warning scheme (no direction, no object).

In interviews participants confirmed the usefulness of warning direction cues. Additionally, participants would appreciate the presentation of visual warnings in the windshield, e.g. LED-Bar or Head-Up display, instead of presenting them in the cluster display. The warning tone was experienced as a useful complement to the visual warning. For unnecessary warnings, the hazard visibility was reported as an important factor for the acceptance of the warnings.

4.4 Study 2 Discussion

Study 2 compared 4 warning schemes to analyze the effects of “Warning direction” (no direction, with direction) x “Warning object” (no object, with object). In an urban test track, 24 participants responded to early warnings and the corresponding hazardous pedestrians, cars and bikes. Unnecessary warnings were also included in the test track. The implemented warnings had a warning onset of 3.8 s (TTA) for lateral warning scenarios and 3.8 s (TTC) for frontal warning scenarios. Each of the 24 participants drove an individual permutation of 4 driving blocks, corresponding to the warning schemes.

Participants benefited from warnings with direction in **lateral warning scenarios** as suggested by the hypothesis. For these scenarios, results show an influence of “Warning direction” on all dependent variables. On the contrary, “Warning object” had only few effects on the measured variables, yet, there was an interaction especially for the time to hazardous object fixation.

Figure 4.33 illustrates an overview of sequential glance steps until visual fixation of hazardous objects in lateral scenarios of Study 2. The warning schemes had no effect on the time to HMI fixation and the duration of HMI glance. Participants needed about .7 s to fixate (look at) the HMI and .4 s to observe the visual warning HMI (glance duration). The time participants needed to fixate the HMI indicates that they shortly evaluated the driving scene after the auditory warning was broadcasted and subsequently looked at the visual warning HMI. Orienting the glance to the speedometer should take the participants about .2 to .5 s (see section 2.3.4), thus participants evaluated the driving scene for approximately .2 to .4 s before watching the visual HMI. The glance duration for watching the HMI is comparable to the glance duration which is needed to check the speedometer. After participants finished watching the HMI, the warning schemes had a clear effect on the time to hazardous object fixation.

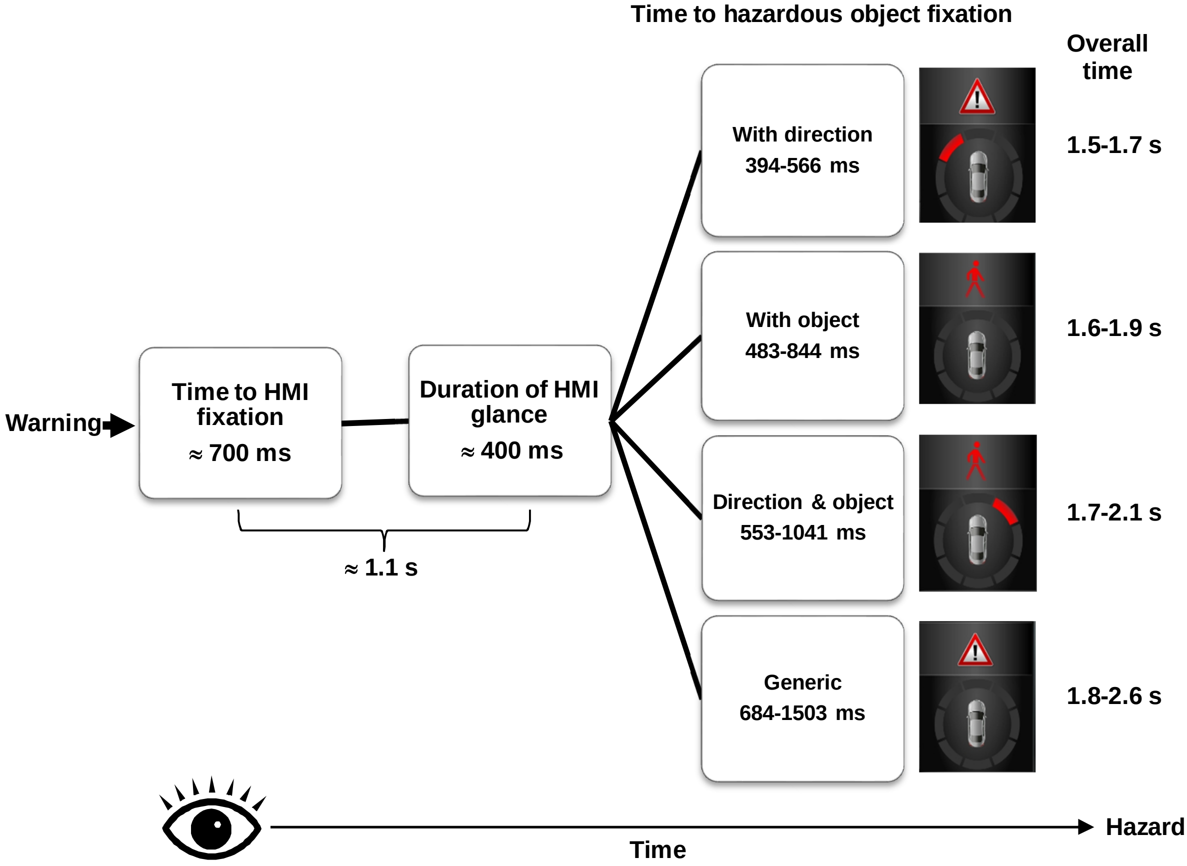

Figure 4.33: Duration until participants fixated the hazardous object in lateral scenarios, separated by the warning schemes and ordered by the overall time until hazardous object fixation. The overall time until fixation of hazards is separated in sequential steps: time to HMI fixation, duration of HMI glance and the time to hazardous object fixation after HMI glance.

The fastest time to hazardous object fixation (394-566 ms) was found for warnings with direction that did not contain an object cue, overall time until fixation of 1.5 to 1.7 s, see Figure 4.33. The second fastest time to hazardous object fixation was achieved by warnings with object and no direction cue, 483-844 ms. A very interesting finding is the interaction for the combination of warning with direction cues and warning with object cues which led to a slightly slower time to hazardous object fixation (553-1041 ms) compared to warnings which contained only direction or object cues. Regarding the time to hazardous object fixation, the effects of warning direction and warning object cues were not additive, as supposed by the hypothesis. However, the slower hazardous object fixation for the combination of warning direction and warning object cues in comparison to the single warning cues was not expected. It seems that cognitive processes for visual attention and perception of the participants took longer to process combined warning cues compared to single ones. In the context of combined expectancies paradigm (e.g., Kingstone, 1992), warning direction and warning object cues should have differing validity to produce such effects. However, for Study 2 the validity of both warning cues was equal. Moreover, the dynamic context of the scenarios or the design of the visual HMI may have affected the attentional processing and led the interaction effect of warning direction and warning object cues for the time to hazardous object fixation.

As the hypotheses suggested, the generic warning scheme (no direction, no object) led to the slowest time to hazardous object fixation, 684-1503 ms, see Figure 4.33. Aside to their urgency, generic warnings did not provide any additional cues which could assist participants in spotting the hazards. The consequence was a slower fixation of hazards, especially for hazardous bike scenarios. Lateral approaching bikes were difficult to spot by the participants because of their size and the associated possibility to get occluded by the A-pillar. This may explain the pronounced effects for the hazardous bike scenarios.

The overall time until participants fixated the hazards after warning onset in lateral scenarios is in the range of 1.5 to 2.6 s. For warnings which contained only direction or object cues, the needed time until fixation stays in range of 1.5 to 1.9 s and indicates that participants had the time to brake after the fixation of the hazards, especially if the brake reaction TTA is considered (see section 4.3.1.1). On the contrary, for the generic warnings (no direction, no symbol) participants needed from 1.8 to 2.6 s to fixate the hazards, indicating that they did not fixate the hazards before braking. Furthermore, for warnings with direction and object cue, both was the case, participants started braking before or after the hazard fixation. Apart from the interaction of warning direction cues and warning object cues, the ability of warning direction cues to orient the drivers' gaze and attention was confirmed corresponding to the findings of Study 1, Ho & Spence (2009) and Naujoks (2013), see section 2.3.3.

As proposed by the hypothesis, warnings with direction may have led to a behavior that was more adapted to the situation than warnings without direction (lateral scenarios). This finding is based on the combined evaluation of the time to hazardous object fixation, the accelerator pedal and brake reaction times, the maximum brake pedal position, the number of collisions and the warning usefulness ratings. For warnings with direction, participants fixated the hazardous objects earlier, but responded slightly later with interfacing the accelerator pedal and brake pedal, compared to warnings without direction. In this context, the main question is: Why did participants respond later, even though they spotted the hazards earlier? It is very likely that drivers adapted their behavior to the situation. In this case, participants spotted the hazards and intentionally decided to start a delayed braking response which is more appropriate to the situation. The main reason therefore is the early warning onset of the implemented warnings. For late warnings, a high brake reaction TTA / TTC would have been an appropriate driver's respond (more distance to the hazard), but for early warning the distance to the hazard is already higher than needed to avoid a collision. Thus, a smaller TTA / TTC may be interpreted as more appropriate response regarding early warnings.

First, an adapted participant behavior to the hazards is supported by the similar maximum brake pedal position for the warnings with direction compared to the warnings without direction. Participants did not respond considerably more intensively to the hazards[21], which may have been the case if they were surprised. Second, the comparable collision rates also suggest that participants did not have more difficulties to respond to the hazards for the warnings with direction. Third, if participants would have experienced their collision avoidance behavior more critical or inappropriate due their "late" response, it is very likely that they would have rated the warnings less useful. The opposite was the case, participants rated the warnings with direction more useful than warnings without direction (direct ratings). At last, the interviews of the participants do

[21] Warnings with direction cues led only to slightly higher maximal brake pedal position (difference of 6%) for hazardous cars, compared to warning without direction cues. Besides, "Warning direction" had no effect on the maximal brake pedal position for the implemented hazards.

support the situation adaption hypothesis because the warnings with direction were described more appropriately for the hazardous situations and more usefully than the warnings without direction. Taken together, these results may indicate that participants showed adapted driving behavior to the lateral hazards with the help of a warning direction cue. However, the described adapted driver behavior is an interpretation that has to be validated by further research.

“Warning object” had only few effects on the assessed variables for lateral scenarios. Dependent on the hazardous object, participants stopped at a greater distance (hazardous pedestrians) or closer distance (hazardous car), if the warning contained a warning object cue. In addition to that, warnings with object were rated more useful, if the hazardous object was a pedestrian. For the hazardous car, the warning object cue may have helped the participants to better predict the path of the approaching car and gave them the option to stop later. Furthermore, participants may have experienced hazardous pedestrians as very vulnerable and thus rated warnings with pedestrian symbol as especially useful. In this context, the warning with a pedestrian symbol helped them to stop intentionally at a greater distance to the pedestrian. However, on contrary to the warning direction cues, warning object cues did not lead to effects that clearly support an adapted driver behavior regarding the lateral hazardous scenarios.

As discussed in connection with the time to fixation of hazards, the combination of warning direction and warning object cues led to an interaction. For the combination of both warning cues, participants took longer to fixate the possible hazards as for the single warning cues. However, by regarding the short brake reaction TTA, the low collision rate and the high warning usefulness ratings for the combined warning cues, it is very likely that the participants also slightly adapted their behavior to the situation. This effect was not as large as for the warnings which contained only the direction cues, where participants had more time to respond because they fixated the hazardous objects earlier.

As already shown in Study 1, the warning schemes had only few effects on the assessed measures for **frontal scenarios.** In contrast to Study 1, for Study 2 effects of the warning schemes were found on the time to hazardous object fixation. The reason therefore may be the salience of the visually presented direction cues and the additionally used visual object cues. For hazardous cars and hazardous bikes, warning with direction led to faster time to hazard fixation than warning without direction, yet, only when combined with warnings without object. It seems that the warning direction cue can even facilitate the fixation of hazards in frontal scenarios, when compared to warnings without direction cue. Furthermore, this effect is only present when no warning object cue is presented additionally. This is a similar kind of inhibition effect on the time to hazardous object fixation, which was discussed for the combination of warning direction and warning object cues in the context of lateral scenarios. Additionally, warnings with object cues led to faster fixation of hazardous cars, indicating the effectiveness of warning object cues for a frontal car scenario, where a hazardous car was suddenly parking out in front of the ego-vehicle. Maybe warning object cues are especially helpful, if the driver's view is already oriented frontally and possible hazards are hard to perceive. In this case, object cues help drivers to anticipate effects of hazardous objects which are already in sight of the driver.

In general, warnings with object led to higher direct warning usefulness ratings in frontal scenarios, compared to warnings without object. This effect confirms the experienced usefulness of the direction cues which slightly facilitated the detection of the frontal hazards. However, accelerator pedal and brake reaction times did not differ for the warning schemes in frontal scenarios.

Opposite to the hypothesis, “Warning direction” and “Warning object” showed no clear effect on the number of braking reactions in **unnecessary warning scenarios**. There is only a slight tendency for warnings with direction cues to cause less brake responses than generic warnings or warnings with direction and object cues. An early participant anticipation of possible hazards in unnecessary warning scenarios should have led to less braking responses. Thus, apart from a slight tendency, warning direction or warning object cues did not effectively help participants to anticipate the behavior of relevant objects in unnecessary warning scenarios. In addition to that, driver brake responses to unnecessary warnings may have been learned responses, which were conditioned to the warnings in other warning scenarios.

In general, directly assessed warning usefulness ratings for unnecessary warnings were perceived as little or very little useful and show means in the range of 2.5 to 5 points on the used 10-point scale. Thus, drivers may have understood the cause of the unnecessary warnings (possible hazards) and did not rate them as completely useless, but also not as useful. Furthermore, the usefulness of warnings for unnecessary warning scenarios shows an interaction of "Warning direction" and "Warning object". Warnings with object led to higher usefulness ratings than warnings without object, yet, only without direction cue. It seems that information about the type of an object is more useful, if no direction cue is provided. In contrast, for unnecessary warnings with direction, the warning with object led to lower usefulness ratings than warning without object. Thus, if a direction cue is provided, the information about the type of possible hazardous object can also reduce the warning usefulness ratings.

Moreover, participant comments suggest that the combination of warning direction and warning object cues are mainly effective if the relevant object can be spotted directly (unnecessary warnings). Maybe the time between the onsets of unnecessary warnings until the recognition of the relevant objects by the driver plays an important role regarding the acceptance and evaluation of unnecessary warnings.

The **post ratings of warning usefulness,** which were assessed after driving, showed considerably less differences for the warning schemes than the direct ratings of warning usefulness for the warning schemes. The main reason therefore may be a memory effect. For example, participants did not exactly remember the warning usefulness for single scenarios and thus evaluated the warning schemes with their general preference. This general preference is based on the experience to all four warning schemes and also includes unnecessary warning scenarios. Thus, the post ratings evaluation shows a tendency towards the middle, eliminating the effects which were present in the single scenarios. In concluding it may be stated that the only effect of the post ratings of warning usefulness is found for “Warning direction”. For hazardous pedestrian scenarios, warnings with direction were rated more useful than warnings without direction (post ratings). Thus, warnings with direction cues were evaluated as especially useful for hazardous pedestrian scenarios. In general, post ratings of warning usefulness were in the range of 5.5 to 7 points on a 10-point scale, indicating that the warnings were experienced as moderate useful or very useful.

Even though the warning schemes led to an effect on the driver’s behavior and warning usefulness ratings, **subjective scales** that evaluated the willingness to pay for the warning system and the preference to use the warning system, did not differ between the warning schemes. The reason therefore may be that many participants had no experience with comparable warning ADAS and no clear opinion on them. In addition to that, in the interviews, most of the participants described warning ADAS as nice to have, but not as a desired feature for their own car. However, participants also evaluated the experienced warning ADAS as (very) helpful to avoid collisions. On average participants were willing to pay about 450 € for the experienced warning systems and had a light preference to use the experienced warning systems in their own car. For the trust in the system, the warning scheme location and object (with direction, with object) showed higher scores than the warning scheme object (no direction, with object) and the generic warning scheme (no direction, no object). Thus, higher warning specificity might be associated with higher trust in the system, if the compared warning ADAS have equal warning reliability.

In the interviews, participants mentioned that they would appreciate the presentation of visual warnings in the windshield, e.g. LED-Bar or head-up display, instead of presenting them in the cluster display. Some participants reported they fear the visual warning in the cluster may distract them in their response to the hazards, regardless of the early warning onset. In this context, it is important to mention that the visual cluster warnings of Study 2 have been only so effective because participants were clearly instructed to look at appearing warnings. A presentation of visual warnings in the windshield, e.g. LED-Bar, may be a more desired solution which furthermore decreases the need for accommodation and saves approximately .2 to .4 seconds regarding the visual reaction time of the driver (adapted from typical glance durations of the driver; see section 2.3.4).

Altogether, Study 2 clearly confirms the effectiveness of early warning direction cues to facilitate the visual fixation of hazards, to help drivers adapting their behavior to hazardous intersection scenarios, and to increase the perceived warning usefulness. Early warning object cues, did only lead to minor effects, especially a facilitation of hazard fixations and higher warning usefulness ratings in frontal scenarios. However, the warning object cues did not lead to an adapted driver behavior. The worst performance and warning usefulness ratings were found for complete generic warnings, which did not contain direction and object cues. Regarding this generic warnings, drivers responded with a brake response before fixating the visual objects, maybe because of uncertainties concerning the hazards.

5 Discussion

To develop a concept for the integration of upcoming warning ADAS, which focuses on early collision warnings, two driving simulator studies were conducted and examined the effects of warning specificity. Main questions were whether and how drivers profit from warning direction cues and/or warning object cues for their response to a hazard, and how these cues affect the acceptance of an integrated warning ADAS approach. Furthermore, it was analyzed whether a generalized warning can be used for a cluster of different ADAS concerning the group “warning of collisions” in comparison to more specific warnings. Therefore critical scenarios in rural and urban environment were evaluated, including frontal and lateral (intersections) scenarios. Unnecessary warnings and false alarms have also been taken into account.

In the following, I will discuss the results of the conducted studies in the context of the warning process model, which was introduced in section 2.1.2. Subsequently, section 5.2 will provide recommendations how to integrate upcoming ADAS collision warnings and discuss possible limitations of the findings. At last, section 5.3 closes with a final conclusion.

5.1 Findings in the Context of the Warning Process

The integrative ADAS warning process model, which was introduced in section 2.1.2, illustrates the warning processing steps made in connection with the ADAS and the driver side and provides an overview of different warning cues which may affect the driver’s response to a hazard. In the following I will focus on the warning processing steps of the driver, and discuss the effects of warning cues by associating the findings of the conducted studies, see Figure 5.1. It is very important to notice that these findings were assessed for early ADAS warning with a warning onset of approximately 2 s before the last possible onset. Furthermore, the effects of warning direction and warning object cues were compared to an early generic warning which did not contain more warning cues than an urgency cue.

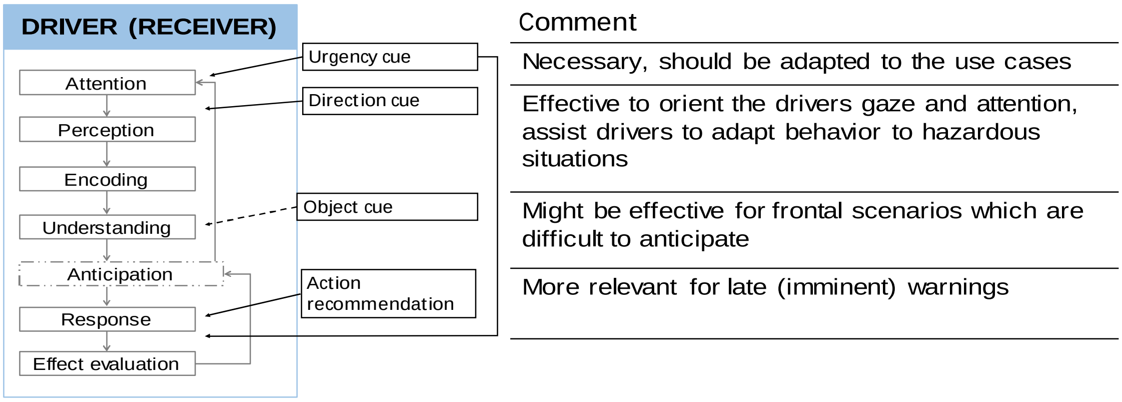

Figure 5.1: Integration of study results of early warning cues into the ADAS warning process model regarding processing steps on the driver side (warning receiver).

As discussed in section 2.3, **warning urgency cues** should represent the urgency of the hazard to lead to an appropriate driver response (e.g., ISO, 2005). The main purpose of warning urgency cues are to alert drivers and redirect their attention to further warning cues of the warning message, or to orient their attention directly to a hazard. For both conducted studies, the warning urgency was adapted to the early warning onset and the scenario criticality regarding different collision scenarios. The implemented auditory urgency cues were evaluated as appropriate to alert drivers and prepare them for further processing of additionally warning cues and the hazardous situations. The conducted studies used a predefined urgency for a cluster of ADAS, which alerted drivers to different kinds of frontal and lateral collisions. Thus, different use cases were addressed with only one urgency level, but they had similarities regarding the urgency, the criticality and the typical driver response, e.g. braking to avoid a collision with a frontal or lateral hazardous bike or pedestrian. In this context, drivers could have perceived the urgency of a warning (tone) as inappropriate for different kinds of hazards and different use cases which belong to the ADAS cluster “warning of collisions”. However, for this assumption no indications were found. In interviews and questionnaires of both studies, no participant described the implemented urgency as inappropriate for multiple use cases or different hazards. Thus, it is very likely that one predefined warning urgency level can be used for a cluster of ADAS, as long the urgency is adapted to the whole cluster of use cases and these ADAS cluster offer similarities for the driver's response and the general urgency level (e.g., Thoma, 2010).

Warning direction cues were examined in both conducted studies. In the first study, auditory direction cues were implemented and in the second study auditory and visual direction cues. A main hypothesis was that warning direction cues can assist drivers in their response to a hazard in different collision scenarios. The ability of direction cues to orient the drivers' gaze and attention to relevant object of the environment could be clearly confirmed. Especially for lateral hazards, e.g. cross traffic at intersection, warning direction cues were effective to direct the driver's gaze to approaching hazards. Additionally, warning direction cues led to slight facilitation for the visual fixation of frontal hazards for some frontal scenarios. These results are in line with findings to spatial attention (Posner, 1980) and driving simulator studies (Fricke, 2009; Ho & Spence, 2009; Thoma, 2010), which mainly analyzed warning direction cues for late warnings (see section 2.3.3). Furthermore, an important difference to late, time critical warnings was found. Regarding early warnings, drivers have additional time to respond to a hazard and may adapt their behavior better to the hazardous situation. Study 2 supported this hypothesis, showing that warning direction cues lead to an adaption of the driver's behavior to lateral warning scenarios. In this context, a combination of visual and auditory warning direction cues was effective to help drivers in their perception and encoding of relevant elements of the environment, as well as controlling their responses to a hazard. For example, starting an adapted braking reaction after waiting until a response is necessary. On the contrary, if warning direction cues were missing, participants needed longer to fixate hazardous objects and responded with braking even before focusing the hazards (not adapted to the situation). The reason for this non-adapted behavior is not known. Maybe drivers had less time left because of the slower perception and were uncertain how to respond, maybe through missing or inaccurate hazard anticipations. Regarding the processing of ADAS warnings, a warning direction cue cannot only influence the attention related processes and perception, but also the further processing steps like understanding, anticipation and the selection of an action response, see Figure 5.1. The central factor seems to be the available time to respond and the environment (situation), which offers additional cues to understand and anticipate a hazardous situation. For early collision warnings, it seems sufficient to orient the drivers' gaze and attention to relevant objects by warning direction cues, to assist them in their action response. An important implication is that warning direction cues should be as accurate as possible in indicating the direction of possible hazards (synchronized) to ease the processing of information which is provided by the environment.

Warning object cues, which indicate the cause of the warning, e.g. hazardous object, were considered to assist drivers in understanding the hazardous situation and help drivers to anticipate possible hazard (see section 2.1.2). Study 2, which examined warning object cues, did not find clear results to support this hypothesis. Visual warning object cues were only effective to facilitate the direction of gaze and attention and this effect was only present, if they were not combined with direction cues. Furthermore, an adaption to lateral warning scenarios was mainly found for the warning direction cues, but not for the warning object cues. Regarding the effects of warning object cues on the attention and the comments given in participant interviews, warning object cues may be especially useful in single (frontal) scenarios which are extremely difficulty to anticipate (also Thoma, 2010). However, these effects could not be measured for the driver braking responses and the associated minimum TTA to the hazards. Additionally, in the interviews nearly all participants reported that they understood the implemented warning symbols, which had a simple shape (see section 4.2.5). When concluding the results of the studied warning cues, it seems that drivers generally use the information they need to anticipate the situation from the environment. It is more effective to tell them where to find this information instead of telling them what they have to find.

For completeness, **action recommendations** have to be mentioned. Action recommendations were not investigated in the conducted studies, but drivers had to choose the right action without getting an action recommendation. In general, action recommendations should help drivers to select the right action response to an emerging hazard. As discussed in section 2.1.2, drivers should have enough time to select the right action response to a hazard by themselves for early warnings. For both conducted studies, participants were able to select the right action response to an early warning. However, additional warning cues modulated the reaction time. For Study 1, these responses were steering (frontal scenarios) and braking, and for Study 2 only braking. Because participants had to brake in most of the scenarios, the number of possible action responses was very limited. Thus, the main task for the participants was not only to select the right action response to a hazard, but controlling it, e.g. adapting it to the hazardous situation. This control task was mainly affected through the early warning cues (direction and/or object cues) which helped drivers to attend to and to perceive possible hazards. Thus, they also should have influenced the processing steps of understanding, anticipation and action response. In contrast to the examined early warnings, late (imminent) warnings highlight the need of an action recommendation because drivers may not have the time or the right anticipation to select a suitable action response to a hazard by themselves.

Even if drivers have some time left to respond to a hazard (1-2 s), specific visual warnings which include location and warning object cues, do not lead to better driver performance than warnings which include single warning cues only. Study 2 found **interaction effects** for warning direction and warning object cues regarding the processing steps of the attention and perception of the driver. The combination of direction and warning object cues led to slower fixation of hazards than warning direction cues or warning object cues only. However, for the driver's behavior, a slight adaption to lateral warning scenarios was also found for the combined warning cues. These results show that effects for combined visual warning direction and object cues are not additive and furthermore may lead to disadvantages when compared to single warning cues, e.g. warning direction cues. The reason may be the design of the implemented visual HMI and the associated attentional processing of the driver. Even if a visual HMI that contains combined warning direction and object cues is understandable, attentional facilitation effects may be smaller for combined cues than for single warning cues. Regarding object oriented attention (e.g., Desimone & Duncan, 1995), the visual warning direction and warning object cues for themselves may not have been recognized as linked features. Furthermore, the visual direction cues and the visual object cues were symbolic representations (endogenous cues), which might have led to interference in the context of attention related processes and warning encoding. According to Kingstone (1992) direction and object cues are processed parallel and may interference on different attentional processing levels. Moreover, the complex interaction between the driver and his environment might promote the interaction effects between different warning cues.

As an **overview** of the discussed findings of Study 2, Figure 5.2 shows the effects of warning direction and warning object cues compared to a generic warning (baseline) and among each other. In addition to the discussed effects on attention and driving behavior, Figure 5.2 also illustrates the effects of warning cues regarding warning usefulness and brake responses in unnecessary warning scenarios and the evaluated warning usefulness which was assessed directly and after driving.

	Effects of warning cues compared to a generic warning and among each other		
Effects on	**Direction cues**	**Object cues**	**Direction & object cues**
Attention	**+++**, for lateral scenarios **++**, for frontal scenarios	**++**, for lateral **+**, for single frontal scenarios which are difficult to anticipate	**+**, lateral scenarios **+**, for frontal scenarios *Interaction effect of both cues*
Driving behavior	**++**, for lateral scenarios **adapted to situation**	**0**, not more adapted than for generic warnings	**+**, for lateral scenarios **adapted to situation**
Warning acceptance and driver response regarding unnecessary warnings	**+,** less negative effects on warning acceptance Descriptively tendency to less braking responses	**+,** less negative effects on warning acceptance	**0,** comments: only less negative effects on warning acceptance if objects are easy to perceive
Warning usefulness ratings in scenarios	**++**, for lateral scenarios **0**, for frontal scenarios	**0,** for lateral scenarios **+**, for frontal scenarios	**+++,** for lateral scenarios **+**, for frontal scenarios
Warning usefulness ratings after driving	**+,** especially for pedestrian scenarios	**0**, not better than generic warnings	**+,** especially for pedestrian scenarios

Figure 5.2: Effects of warning direction and warning object cues compared to a generic warning (baseline) and among each other regarding an integrative warning HMI for collision avoidance. The generic warning contained no direction cues or object cues and performed worse in all variables. Findings are based on Study 2 of this thesis, which used a visual and auditory HMI for the direction cues, and visual HMI for the object cues. **0** indicates no difference to the generic warning. Each **+** indicates better value for a comparison between the different warning cue variants or the generic warning. For example, **+++** regarding the effects of the direction cues on attention in lateral scenarios indicates: The direction cues were (significant) better than generic warning, object cues and both cues. Additionally, if cues were better than two other variants which did not differ, only one **+** was given, e.g. effect of warning direction cues on warning usefulness ratings after driving.

Regarding **unnecessary warnings**, which were examined in Study 2, warning direction cues and warning object cues led to less negative effects on warning acceptance compared to a generic warning, see Figure 5.2. Furthermore, warning direction cues showed a descriptive tendency to less brake reactions than generic warnings and participants described them as useful to spot the relevant objects. In contrast, the combination of both cues was not better evaluated than a generic warning. Participant comments indicated that the combination of warning direction and warning object cues may only lead to less negative effects on warning acceptance if the hazardous objects are easy to perceive (single scenarios). In addition to illustrated effects of Figure 5.2, Study 1 showed that warning direction cues can lead to more pronounced visual search behavior in false alarm scenarios, compared to generic warnings without direction. This visual search behavior may not necessarily be a disadvantage, as long as other unintended driver responses like brake reactions do not occur more often (see section 3.4).

An interesting finding is that effects of warning cues on warning usefulness ratings after driving were generally much lower than for warning usefulness ratings during the test driving, see Figure 5.2. As discussed in section 4.4, memory effects, unnecessary warnings and general preferences might have led to this evaluation effect. As a result, only warnings with direction cues had a positive effect on the warning usefulness ratings after driving, yet, only for hazardous pedestrian scenarios. This effect was present for the direction cues only and the combination of direction and object cues.

The comparison of the effects of warning direction and object cues (see Figure 5.2) leads to the conclusion that warnings with direction cues seem to offer more benefits for an integrated warning approach. Especially for the driver's attention and acceptance of unnecessary warning, warning direction cues show advantages compared to the warning object cues or the combination of both cues. An exception are the higher warning acceptance ratings in critical warning scenarios of the combined warning cues, compared to the warning direction or warning object cues only.

In general, the examined warning cues had an impact on the acceptance regarding the warning ADAS, but not necessarily on the desire to buy and use these experienced ADAS in the own car. The main reason therefore may be the missing experience of the participants with these ADAS, and the evaluation of ADAS as nice to have but not as important feature for the own car. Furthermore, participants may evaluate collision as rare event and thus a collision warning system as less important. Regarding this finding, new ADAS have to be promoted and better explained to possible customers.

Altogether, the implementation of warning direction cues to an integrative ADAS warning concept is a central point. More specific warnings, which additionally include elements like warning object cues, may not lead to better driver adaption to hazardous situations than for warnings with direction cues only. Additionally, warning object cues have only limited influence on the overall ADAS acceptance regarding early warnings. In general, participants can understand and effectively use an integrated warning concept for multiple hazards and collision scenarios. In the following, I will provide recommendations how to integrate future warning ADAS to collision using the discussed findings.

5.2 Recommendations for Warning Integration

Based on the discussed findings of this thesis, Figure 5.3 shows an overview of recommendations for integrating multiple ADAS warnings regarding collision avoidance. It takes into account two warning timings and the major warning cues which can be included into a warning. The warning timings are separated into two categories, the first warning onset category (early) is T0 + 2 s TTC / TTA, which is the warning onset timing that was examined in this thesis. The second warning onset category (T0) is the last possible onset for a warning, e.g. for a host-vehicle speed of 50 kph, a TTC / TTA of about 1.8 s between host-vehicle and an obstacle (see section 2.2.3).

Time of warning onset	Urgency cue	Direction cue	Object cue	Action recommendation
T0 + 2 s (early)	Necessary, urgent	**Very effective**	N.n.	N.n.
T0 (late)	Necessary, very urgent	Not necessary for many use cases, but should be included for consistency	N.n.	Effective to assist drivers in their response selection

T0 = Last possible warning onset; N.n. = Not necessary

Figure 5.3: Recommendations for the integrating of multiple ADAS warnings based on the findings of this thesis and based on the literature review in section 2.5.2. Two warning onset and the relevance of different warning cues are shown. The warning onsets are separated into two categories. The first warning onset category is defined with an onset of T0 + 2 s, which indicates the last possible warning onset plus two seconds.

In the following I will describe the presented recommendation for each warning cue regarding the two warning onset categories which are illustrated in Figure 5.3.

For the examined **warning onset at T0 + 2 s**, warnings have to be *urgent* for a cluster of collision use cases. As discussed in section 2.4.1 and 2.5, these use case clusters can be associated with different ADAS but should contain similarities especially regarding the urgency and the needed driver response. Warning *direction cues*, e.g. a visual and auditory HMI which indicate the direction of a hazard, should be included. The conducted studies of this thesis indicate that early direction cues help drivers to adapt their behavior to lateral hazards, e.g. cross traffic at intersections, and are also useful to warn drivers against frontal hazards. Warning direction cues should be highly synchronized with the hazardous object and indicate its position with high accuracy, e.g. fast adapt to direction changes and a resolution of about 45° for each direction segment. Warning *object cues*, e.g. the symbol of a hazardous car or bike, were not necessary for early warning onsets at T0 + 2 s. Regarding Study 2, the combination of warning direction cues and warning object cues led to disadvantages for the attentional processing of the driver and the acceptance of unnecessary warnings, compared to warning direction cues only. Additionally, it may be easier for future sensor technologies to detect the hazard direction more accurately than the type of a hazardous object. In case, the integrated warning system has not the ability to detect or display warning direction cues, but is able to present warning object cues, the warning object cues should be displayed. Object cues may lead to better driver performance and higher warning acceptance compared to a generic warning without direction and object cues. For early warning onsets at T0 + 2 s, *action recommendations* may not be necessary. For this warning timing, it seems to be sufficient to orient the driver's attention to possible hazards and thereby offer him the possibly to choose the action response by himself.

For the **warning onset at T0,** warnings have to be *very urgent* for a cluster of immanent collision use cases. For these use cases, drivers can usually perceive hazards with frontal attention because of the close time distance to the hazards. Thus, warning *direction cues* may be less effective than for T0 + 2 s or not necessary (Thoma, 2010; R. Zarife et al., 2012). However, for consistency of an integrated warning HMI, warning direction cues should be also present for a warning onset at T0. *Warning object cues*, were found to be not necessary for late warning onsets regarding multiple ADAS use cases (Thoma et al., 2009; Thoma, 2010). For these onsets drivers may not have the time to process or effectively use warning object cues. *Action recommendations* are useful for a late warning onset (T0), if drivers are unsure how to respond or wait too long to initiate an action response (Petermann-Stock & Rhede, 2013, p. 283).

For the integration of upcoming warning ADAS regarding the ADAS cluster “warning of collisions”, different **HMI devices** have to be considered. The reported findings were mainly based on a combination of visual (cluster) and auditory warning HMI. However, Naujoks et al. (2012) showed that comparable effects can be found for the combination of a head-up display and auditory HMI which also highlight the effectiveness of visual warning direction cues to early collision warnings. Generally, warning elements like a (reflective) LED-Bar or head-up display may reduce the need for accommodation and save glance time when compared to a cluster presentation (see section 2.4.2).

In the context of a two-step **warning cascade**, an early warning (T0 + 2 s, step one) should include direction cues. In the second warning step (T0), these warning direction cues may be combined with an action recommendation. As suggested by Petermann-Stock & Rhede (2013) an automatic intervention should follow if the driver does not respond to the action recommendation.

Limitations. The examined scenarios covered only maximum ego-vehicle speeds of 80 kph (rural scenarios) and 50 kph (urban scenarios). For higher speeds, warning cues might interact differentially. For considerably lower speeds, the examined warning cues may be less effective, but it should be also easier to avoid a collision. The evaluated lateral scenarios focused on crossing hazards which had an angle of +/-54° (Study 1) and +/-36° (Study 2) to the center of frontal view at warning onset. Furthermore, the conducted studies only examined a warning onset of approximately T0 + 2 s. Another point is the warning reliability, which was homogenous for the examined warning ADAS cluster. If the reliability of the associated use cases is inhomogeneous, e.g. frontal warnings have a completely different reliability than lateral warnings, it may affect the warning effectiveness of the whole integrated warning system.

5.3 Conclusion

This thesis provides recommendations which warning elements should be included into future ADAS warnings in favor of an integrated warning approach. Especially early warning direction cues have a high potential to assist drivers with an ADAS warning cluster which covers warning of collisions. In contrast, warning object cues seem to be less important for the drivers' performance and acceptance regarding early collision warnings. For future research purposes, the examination of warning devices like a (reflective) LED-bar can be important because these devices may be especially suited to incorporate direction cues into an integrative warning concept. Furthermore, the next step to develop an integrated warning concept would be the implementation of the findings into a real vehicle prototype in combination with upcoming technologies like C2X communication. As the results of this thesis also indicate, an important task will be to promote and explain future ADAS to possible customers. This is all the more important because these systems will be introduced into the market by Euro NCAP requirements and are a prerequisite on the way to automated driving.

6 Bibliography

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7 Appendix A

Table 7.1: Overview to a selection of possible ADAS clustering factors.

Clustering Factor	Example	Notes
Driving task level of ADAS interaction	Stabilization (e.g., EB) Guidance (e.g., ACC, FCA) Navigation (e.g., NAVI)	
Typical attentional path of the driver in ADAS use case	Left or right mirror (e.g., BSW) Frontal (e.g., FCA)	
Direct driver response in ADAS use case	Braking (e.g., FCA) Steering (e.g., LCW)	
Behavioral goal of driver in ADAS use case	Collision mitigation (e.g., FCA) Lane keeping (e.g., LKA)	
ADAS spatial orientation	Frontal (e.g., FCA) Lateral (e.g., LKA) Rear (e.g., RCA)	
Typical ADAS response time	High (e.g., ESC) Low (e.g., LCA)	See Freymann (2006)
Typical driver response time	Fast (e.g., FCA) Slow (e.g., Weather warning)	
ADAS automation level	Requires response (e.g., FCA) Semi-automated (e.g., ACC) Highly-automated (e.g., ACC & LK) Fully-automated (no driver response needed)	
ADAS associated hazard type	Pedestrians (e.g., PW) Cars, objects (e.g., FCA)	
Typical criticality of ADAS use case	High (e.g., FCA) Low (e.g., weather warning)	
Typical environment of ADAS use case	Highway (e.g., ACC) Urban (e.g., GLOSA)	

Acronym	Description	Acronym	Description
ACC	Adaptive Cruise Control	LCW	Lane Change Warning
BSW	Blind Spot Warning	LKA	Lane Keep Assist
EB	Emergency Brake Assist	NAVI	Navigation system
ESC	Electronic Stability Control	PW	Pedestrian Warning
FCA	Frontal Collision Alert	RCA	Rear Cross Traffic Alert
GLOSA	Green Light Optimized Speed Advisory		