The Influence of Anticipation and Warnings on Collision Avoidance Behavior of Attentive Drivers

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For Martina.

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Contents

List of Figures

List of Tables

List of Abbreviations

ABC	Anticipative Behavior Control
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ANOVA	Analysis of Variance
BRT	Brake Reaction Time
CAS	Collision Avoidance Systems
CR	Correct Reaction
CWS	Collision Warning System
DAS	Driver Assistance System
FA	False Alarm
FCW	Forward Collision Warning
GM	General Motors
HMI	Human Machine Interface
HRU	Hazardous Road User
HT	Headway Time
HUD	Head Up Display
ISO	International Organisation of Standardization
MOSAIC	Modular Selection And Identification For Control
OEM	Original Equipment Manufacturer
PPV	Positive Predictive Value
ROC	Receiver Operating Characteristics
RT	Reaction Time
SA	Situation Awareness
SDT	Signal Detection Theory
SSD	Stopping Sight Distance
TTC	Time to collision
UM	Urgency Mapping

Zusammenfassung

Einfluss von Antizipation und Warnung auf das Kollisionsvermeidungsverhalten aufmerksamer Fahrer

Die vorliegende Arbeit beschäftigt sich mit Kollisionsvermeidungsverhalten im Straßenverkehr. Die Hauptfragestellung der Arbeit erforscht die Bedingungen, unter welchen Menschen Kollisionsvermeidung gut beherrschen, und stellt dabei den Anteil der Antizipation in den Vordergrund. Ein weiterer Hauptpunkt der Arbeit ist die Frage, ob in den Situationen, in denen Fahrer kein angemessenes Verhalten zeigen, ein Frontkollisionswarnsystem unterstützend wirkt. Der Begriff Frontkollisionswarnung wird im Folgenden von dem Englischen Begriff "Front Collision Warning" als FCW abgekürzt.

Frontkollisionswarnsysteme arbeiten dergestalt, dass sie versuchen, mittels einer Warnung (z.B. einen akustischen oder visuellen Reiz) zum einen die Aufmerksamkeit des Fahrers in Richtung der Gefahr zu leiten und zum anderen ein geeignetes Vermeidungsverhalten auszulösen. Als Hauptursache für Auffahrunfälle konzentriert sich die Wissenschaft, die Frontkollisionswarnungen untersucht, auf Unaufmerksamkeit und Ablenkung des auffahrenden Fahrers. Man geht davon aus, dass die Unfallschwere zunimmt, wenn der Fahrer abgelenkt ist, da ein abgelenkter Fahrer verspätet oder gar nicht reagiert. Dieses Manko soll die FCW beheben. Um die Effektivität der FCW in diesen besonders kritischen Situationen sicher zustellen, wurde ein großer Anteil der Studien mit abgelenkten Fahrern durchgeführt. Untersuchungen zu Ursachen und möglichen Vermeidungsstrategien hingegen von Unfällen mit aufmerksamen Fahrern sind kaum verfügbar, obwohl Unfalldatenbanken und Feldtests zeigen, dass 40-60% der Fahrer kurz vor einem Auffahrunfall auf die vor ihnen liegende Fahrszene schauen. Daher haben auch nur wenige Veröffentlichungen Theorien zu den Hintergründen verunfallender aufmerksamer Fahrer entwickelt.

Anhand der Literatur wird herausgearbeitet, dass eine Hauptursache für verspätete Vermeidungsreaktionen eine falsche Aufmerksamkeitsausrichtung des Fahrers ist. Des Weiteren wird dargestellt, dass höhere Aufmerksamkeitsprozesse stark von der Situationsinterpretation und -antizipation beeinflusst werden. Daraus wird die Hypothese abgeleitet, dass aufmerk-

same Fahrer dann verspätet reagieren, wenn es ihnen entweder nicht möglich ist, die Gefahr vorherzusehen oder der Fahrer die Situation falsch einschätzt. Falls dies zutrifft und eine fehlende oder fehlgeleitete Antizipation die Ursache für Unfälle darstellt, müsste eine FCW vorteilhaft wirken, wenn diese schnell und leicht verständlich ist. Eine so gestaltete FCW könnte die Situationswahrnehmung des Fahrers ergänzen. Es wird die Hypothese aufgestellt, dass FCW fehlende oder fehlgeleitete Gefahrenantizipation des Fahrers kompensieren können.

Aktuell werden FCW Systeme mit unterschiedlichen Warnstrategien von verschiedenen Fahrzeugherstellern verkauft. Außerdem existieren zahlreiche wissenschaftliche Empfehlungen zur Auslegung einer FCW. Um die Auswirkungen verschiedener Warnungsauslegungen auf Verhaltensmaße und subjektives Empfinden zu testen, wurde ein Experiment in einem Fahrsimulator durchgeführt. In einem vollständig abhängigen Versuchsdesign wurden 10 Warnungen gegeneinander getestet. Dabei setzten sich die 10 Warnungen aus fünf Modalitäten (visuell, akustisch und drei haptische Lösungen) mit je zwei Intensitäten zusammen. Generell zeigte sich, dass physikalisch intensivere Warnungen zu schnelleren Reaktionen führten. Weiterhin ergaben die Daten, dass von den fünf Modalitäten die drei Varianten akustische Warnung, Lenkradvibration und Bremspuls zu den schnellsten Reaktionen führten. Die getestete Sitzvibrationswarnung, welche im Sitz unter den Oberschenkeln der Probanden vibrierte, führte zu langsameren Reaktionen und die visuelle Warnung erzielte die längsten Reaktionszeiten. Die drei Warnungen, welche untereinander deutlich unterschiedliche Resultate in objektiven wie subjektiven Maßen erreichten, wurden im Folgeexperiment weiter verwendet. Diese waren die intensive visuelle Warnung, die intensive Sitzvibration und die intensive akustische Warnung (2000Hz Sinuston).

Hauptuntersuchungsgegenstand des zweiten Experiments ist die Interaktion zwischen verschiedenen Gütestufen der Gefahrenantizipation und der An- bzw. Abwesenheit von FCW in verschiedenen Fahrsituationen. Des Weiteren war die Studie so geplant, dass der Einfluss der drei unterschiedlichen Warnungen aus Studie 1 überprüft werden konnte. Um die verschiedenen Gütestufen der Antizipation zu realisieren, wurden komplexe Stadtszenarien im Fahrsimulator umgesetzt. Das Verhalten des umgebenden Verkehrs wurde in einer Weise modifiziert, dass es das Situationsbewusstsein des Fahrers beeinflusste. Der umgebende Verkehr erlaubte es dem Fahrer, (1) die Gefahr vorherzusehen, (2) die Gefahr nicht vorherzusehen oder leitete (3) die Antizipation des Fahrers dadurch fehl, dass ein weiterer, irrelevanter Verkehrsteilnehmer eingeführt wurde.

Die Ergebnisse dieser Studie bestätigen die Hypothese, dass die Güte der Gefahrenantizipation den größten Einfluss auf das Fahrerverhalten in einer drohenden Unfallsituation hat. Die Ergebnisse deuten weiter darauf hin, dass FCW-Systeme aufmerksamen Fahrern messbar helfen, wenn sie die Gefahr nicht antizipieren oder sogar die Situation falsch einschätzen. Die positive Wirkung ist bei der getesteten akustischen und haptischen Warnung besonders ausgeprägt. Auffällig war, dass der negative Einfluss der fehlenden oder fehlgeleiteten Antizipation bei plötzlich auftauchenden Gefahrenobjekten deutlich geringer war, als wenn diese längere Zeit sichtbar waren, bevor sie zur Gefahr wurden. Es wird davon ausgegangen, dass dieser Effekt aufgrund visueller Eigenschaften der Gefahrenobjekte ausgelöst wird. Bei den plötzlich auftauchenden Gefahren wird davon ausgegangen, dass diese einen lower-level Aufmerksamkeitsprozess auslösen, welcher im Konflikt zu top-down Aufmerksamkeitsprozessen steht, die die Antizipation steuern.

Ein wichtiges Ergebnis der zweiten Studie ist, dass (Front-) Kollisionswarnungen erst vom Fahrer gelernt werden müssen, damit sie sich positiv auf die Kollisionsvermeidung auswirken können. Die Teilnehmer mit Warnung reagierten beim ersten kritischen Ereignis langsamer als die Teilnehmer ohne Warnung. Dieser Zusammenhang war bei Probanden mit visueller Warnung besonders ausgeprägt. Später im Experiment war die Probandengruppe mit Warnung konstant schneller als die Gruppe ohne und zeigte einen klaren Vorteil einer gelernten FCW.

Somit legen die Ergebnisse dieser Simulatorstudien nahe, haptische oder akustische Warnungen als primäre Warnmodalitäten in drohenden Auffahrsituationen zu verwenden. Das Charakteristikum visueller Stimuli, die visuelle Aufmerksamkeit auf sich zu ziehen, ist Segen und Fluch zugleich, wenn sie als Warnung eingesetzt werden. Es wird vorgeschlagen, eine visuelle Komponente als zusätzliches Warnelement zu verwenden. Dabei sollte der Einsatz zeitlich so stark wie möglich begrenzt werden, um die Aufmerksamkeit des Fahrers auf die frontale Szene zu richten, ohne ihn dabei länger als nötig von dieser abzulenken. Fahrzeughersteller versuchen, so viele unnötige Warnungen wie möglich zu vermeiden, da davon ausgegangen wird, dass diese den Kunden stören. Daher wird häufig geplant, FCW zu unterdrücken, wenn man beispielsweise über ein Fahrerbeobachtungssystem wüsste, dass der Fahrer nach vorne schaut. Die Ergebnisse dieser Arbeit sprechen gegen diesen Ansatz. Wenn ein Fahrer in eine kritische Situation gerät, welche z.B. von einem FCW-System durch eine niedrige Time-To-Collision (TTC)[1] repräsentiert wird, sollte er immer eine Kollisionswarnung erhalten. Die wichtigsten Argumente für diese Aussage sind folgende:

- Nur weil der Fahrer auf die Straße schaut, heißt das nicht, dass er das korrekte Situationsbewusstsein hat.
- Der Fahrer muss die Bedeutung der Warnung erlernen.
- Der Fahrer wird von der Warnung nicht gestört sein, solange er die Situation selbst als kritisch einschätzt.

[1] TTC: Aus der Relativgeschwindigkeit zweier Objekte errechnete Zeit bis zur Kollision unter Annahme konstanter kinematischer Bedingungen

Executive Summary

This thesis deals with collision avoidance. Focus is on the question of under which conditions collision avoidance works well for humans and if drivers can be supported by a Forward Collision Warning (FCW) System when they do not react appropriately.

Forward Collision Warning systems work in a way that tries to focus the driver's attention in the direction of the hazard and evoke an avoidance reaction by some sort of alert (e.g., tone or light). Research on these warning systems generally focuses on inattention and distraction as the cause for crashes. If the driver is inattentive, the results of a crash are thought to be worse as the driver's reaction is belated or might not mitigate the crash at all. To ensure effectiveness in the worst case, most of the experiments studying FCW systems have been conducted with visually distracted drivers. Research on the cause and possible countermeasures for crashes of attentive drivers are hardly available, although crash databases and field operational test data show that 40-60% of the drivers look at the forward scene shortly before they crash. Hence, only a few studies elaborated on ideas about the reasons for crashes with attentive drivers.

On the basis of the literature, it is worked out that one reason for delayed avoidance behavior can be an incorrect allocation of attention. It is further elaborated that high level attention processes are strongly influenced by interpretation of the situation and the anticipation of future status. Therefore, it is hypothesized that alert drivers react later when they can not foresee a potential threat or even when they misinterpret the situation. If the lack of threat anticipation or incorrect anticipation is a reason for crashes, a FCW system could be a great help, when the FCW is easily comprehensible. It is hypothesized that a FCW can compensate for missing threat anticipation in the driver.
There are several implementations of FCW already on the market and a lot of scientific recommendations published on how to design a FCW. To determine how several possible implementations affect behavioral and subjective measures, ten different warnings have been tested in a driving simulator set-up. The ten warnings are composed of five different modalities (visual,

audible, and three haptic variants), which were presented in two intensities each. Generally, high intensity warnings of all modalities lead to faster reactions. Reaction times to the warning types Steering Wheel Vibration, Tone, and Brake Pulse are the fastest. The haptic seat warning, which vibrates under the driver's thighs, comes next and the visual warning elicits the slowest reactions. Three warnings, with distinct differences in resulting reactions and subjective assessments, were further used. These are a visual warning, a haptic seat warning, and a 2000 Hz tonal warning.

Main interest in the second experiment is the interaction of different quality levels of threat anticipation in different driving scenarios and the presence particularly the absence of a Forward Collision Warning. The study was also designed to identify whether the influences of the different warning types found in the first study are still valid in more realistic situations. A complex urban driving scenario was employed that allows the participants to gain only certain levels of correctness of threat anticipation. Behavior of the surrounding traffic was modified to influence the participants' situational awareness. The surrounding traffic behavior allowed the threat to be anticipated (1), not anticipated (2), or by introducing a second but irrelevant traffic stimulus, the driver's anticipation was misled (3).
The results of this study show that the level of threat anticipation has the largest influence on driver behavior in an imminent crash situation. The results further suggest that FCW systems – especially warnings of audible or haptic modality – can help attentive drivers who do not anticipate a threat or misinterpret a situation. The negative influence of missing or mislead threat anticipation on objective measures was small when the threat appeared suddenly. This is thought to be due to the visual appearance of the introduced threat. It is assumed that this type of stimulus triggers a lower level attentional process, as opposed to a top-down attention process controlled by an anticipatory process. In the other scenario types such a lower level process may not be triggered.
An important result of the second study is that (Forward) Collision Warnings have to be learned. Participants with warnings reacted slower than participants without any FCW in the first critical event. Participants with a visual warning reacted particularly slow. Later in the experiment, the probands with warnings were constantly faster than their counterparts without them.

Hence, the results of this study suggest that a haptic or audible modality should be used as a primary warning to the driver. The characteristic of visual warnings to draw the visual attention is both a blessing and a curse. It is suggested to use the visual warning component for only a short period of time to attract the driver's attention to the forward scene, but then end the display to not further distract him. Car manufacturers try to avoid as many unnecessary alarms as possible. If driver monitoring would be available, it is often planned to suppress warnings when the driver is looking through the windshield. The results suggest not to do so. If a driver reaches a critical situation represented by a low Time-to-collision (TTC) or a high need to decelerate, he should always get a warning, unless he is already braking or steering. The most important arguments for this are:

1. Looking at the street does not mean that the driver has the correct situational awareness.

2. The driver has to learn the meaning of the warning.

3. The driver will not be annoyed by a warning when the situation is considered critical.

Chapter 1

Introduction

More than 4000 people were killed in German traffic accidents in 2009 (Statistisches Bundesamt Deutschland, 2010) and more than 41,000 people are killed in motor vehicle crashes on U.S. roads every year (NHTSA, 2008). Knowledge of the driver's status before a crash may be useful for the development of collision avoidance systems. Driver attention status is reported in 58.5% of crashes from the Crashworthiness Data System (Stutts, Reinfurt, Staplin, & Rodgman, 2001). The statistics based on this data show that drivers state to have been attentive before the crash in 75% of these cases.

Klauer, Dingus, Neale, Sudweeks, and Ramsey (2006) analyzed driver gaze behavior on video data of the so-called 100-car-study. In this Field Operational Test data they found a high number of attentive drivers that were involved in crashes. In 40% of the recorded incidents, near-crashes, and crashes, drivers were looking straight ahead in the last 5 seconds before the event. But even in the 60% of cases when drivers were not classified as looking at the forward road scene, one can argue that a lot of drivers might have been attentive. This is because these 60% include drivers looking to the left or right of the forward scene, checking mirrors, and glancing at the instrument cluster. One can argue that these drivers were attentive but just not focusing on the direction of the hazard. Defining an attentive driver is not easy, particularly when one has to judge overt behavior. The research community agrees, on the one hand, that a driver looking away from the forward roadway is an inattentive driver. But, there is also agreement that a driver who is systematically scanning his/her environment (i.e., looking away from the forward roadway) is an attentive driver (Klauer et al., 2006). Altogether, 69% of the 100-car-study drivers included in near-crashes or crashes were looking forward (including +/- 40° the centerline) or checking the instrument cluster in the five seconds before the crash. The gaze data collected suggest that between 40% and 69% of the involved drivers were attentive.

According to Jermakian (2011), crash types relevant for Forward Collision Warning (FCW) systems accounted for 61 to 70% of front-to-rear crashes in the USA, or approximately 1,022,000 to 1,165,000 crashes per year. Of these, 56,000 to 66,000 involved nonfatal injuries and 807 to 879 involved fatal injuries. These numbers look at crashes with cars and trucks only. Hence, research on the causes for rear-end collisions is motivated by the goal of saving lives and reducing economic loss.

The questions at hand are:

- What is the reason for this high number of crashes with attentive drivers?
- Why do drivers look at the frontal scene, but do not react appropriately?
- How many of these crashes could be avoided by better performance of the driver?
- Could this situation be changed with the help of a warning system?

Research on collision avoidance systems for rear-end collisions generally focus on inattention as the cause for crashes. If the driver is inattentive the results of a crash are thought to be worse as the driver might not mitigate the crash at all. Therefore, research and production focuses on worst case scenarios and develop systems that warn the driver of an imminent frontal collision. These systems try to focus the driver's attention in the direction of the hazard and evoke an avoidance reaction by some sort of alert (e.g., tone or light). Therefore, most of the experiments investigating FCW systems in traffic situations have been conducted with distracted drivers (e.g., Dingus et al., 1997; Kiefer et al., 1999; Lind, 2007). Similar studies about the advantages of FCW for alert drivers are not available. Furthermore, only a few studies elaborated ideas about the reasons for crashes with attentive drivers Brown (2005); Muhrer and Vollrath (2010).

To avoid loss, harm, or injury by definition means that the harmful act has not taken place. If avoidance behavior is shown voluntarily this further implies that the person has to have foreseen the harm. This person has to foresee the future state of the situation to know that the avoidance behavior is needed. So, in psychological terms, an anticipation of the harm has to precede any avoidance behavior. Transferred to the driving area, this means: To be able to perceive the elements in the environment within a certain time and space, understand their interrelationship, and anticipate their status in the near future (more in section 2.1.2).

This thesis will deal with collision avoidance and the question under which conditions collision avoidance works well for humans and how or if the driver can be supported by a Forward Collision Warning System. This thesis hypothesizes that anticipation is a key element in avoiding collisions in a dynamic situation. This is true for the human operator as well as any autonomous acting system. Focus here is on the performance and decision making of a human operator or driver. Hence, the question is on how a human can be supported in the task.

Chapter 2

Theoretical Background

This chapter will summarize the research and concepts that deal with driving, collision avoidance, warnings, and the interaction between humans and driver assistance systems. The goal is to understand the behavioral or cognitive change that may be elicited by a Forward Collision Warning (FCW). Therefore, this chapter will focus on the relevant aspects of driving in order to understand the psychological context where warning signals may interfere. Hence, focus will be on collision avoidance in a dynamic environment. For the ease of explanation, a collision will refer to two dynamic objects hitting each other. Then the text will report the results found in warning research and link this back to driver assistance systems.

2.1 Driving and Collision Avoidance

Regarding the human factors of "everyday driving", a lot of scientific information is missing. P. Green (1993) wrote the following, which is still true:

> "...how people actually drive is not well understood. Most of the research has focused on what happens to people when they are involved in accidents and other matters pertaining to crash worthiness, not what happens beforehand (pre-crash). Further, very little is known about what behavior constitutes normal driving."

Generally speaking, driving means to control a moving object in a restricted, dynamic environment. One essential part of moving through the environment is to avoid colliding with other (moving) objects. As this thesis deals with collision avoidance, the following views on driving tasks are presented with this focus.

2.1.1 Theoretical Models of Driving

The operator's/driver's tasks when driving are seen to be organized hierarchically (e.g., Bernotat, 1970; Michon, 1985; Rasmussen, 1983). The tasks are divided into three different stages, which are determined by skill and time. It is essential that the three stages influence each other. The three typical levels are (cf. Bernotat, 1970; Michon, 1985):

1. strategic (or navigation)
2. tactical (or maneuvering)
3. operational (or stabilization)

The strategic level defines the general planning stage of a journey. This means, for example, the choice of route and defining the journey's goals. The strategic level has the longest time constant. At the tactical level, drivers exercise maneuver control in the prevailing circumstances. These maneuvers are obstacle avoidance, gap acceptance, turning, and overtaking, and have a time frame of seconds. Although they are primarily driven by the actual situation, they shall meet the criteria derived from the general goals set at the strategic level. On the other hand, these goals may be adapted to fit the outcome of certain maneuvers. On the lowest level, operational control of the intended maneuvers is accomplished. The operational level is thought to be controlled in milliseconds.
Rasmussen (1983) alternatively determines the following three levels

1. Skill-based behavior
2. Rule-based behavior
3. Knowledge-based behavior

According to Rasmussen (1983), skill-based behavior represents sensory-motor performance during acts or activities which, following a statement of intention, take place without conscious control as automated patterns of behavior. Perceiving a relevant stimulus directly triggers an automated behavior pattern. Rule-based behavior is goal oriented, but structured by "feed forward control" through stored rules. These rules are a composition of several patterns at the skill-based level. The perceived elements from the environment have to be recognized from long-term memory and then interpreted. This recognized situation leads to an association of appropriate tasks. The level of knowledge-based behavior is thought to be needed primarily when no know-how or control rules are available. The operator has to explicitly formulate a goal, based on the analysis of the environment. More than one plan has to be developed and the plan that best fits the goal will be chosen. Predictions of the effects have to be considered.

Collision avoidance is primarily thought to happen at the levels of maneuvering and stabilization, rule-based and skill-based behavior respectively. How is the driver able to fulfill these tasks? The already considered basic models of driving provide a framework in this area. Michon (1985) states that any control of action in driving has to be adaptive. A “mechanic” task fulfillment without a constant check for situational changes is doomed to fail. But a solely data driven concept is also too easy. The driver uses strategies developed in the past and makes assumptions about the future status. For the task of collision avoidance, some projection of the future or anticipation is essential. If a being would only deal with current states, collision avoidance would not be possible. In fact, dealing with any dynamic environment would not be possible.

2.1.2 Role of Situation Awareness and Anticipation

How do experienced drivers manage to drive through complex traffic scenarios? Or more generally, how do humans manage to operate in a dynamic environments? Currently, the most cited framework for this questions is “Situation Awareness”. The term “Situation Awareness” is not a standardized term, but the most accepted definition was made by Endsley (1988, p. 792):

> Situation awareness is the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.

In the definition by Endsley, situation awareness (SA) consists of three levels (see also Figure 2.1). Situation awareness involves perceiving critical factors in the environment (Level 1), understanding what those factors mean, and these have to be matched with the person’s goals (Level 2), followed by the understanding of what will happen with the system/environment in the near future (Level 3). In other words, the third level is anticipation. Originally, the concept was used in the aircraft pilot community. Now it has found its way into many domains where people operate complex, dynamic systems, including, for example, air traffic control, automobiles, and the nuclear power industry. In the automobile traffic environment, the driver has to be aware of critical traffic parameters, such as the speed of their car, location on the street, number of lanes for the direction they are heading and which they have access to, location of other road users, and status of traffic lights. The knowledge of these (and more) facts build Level 1. An important step to situation awareness is the interpretation of these facts by the driver (the traffic light switches to red, the cars moving in my direction should stop). This understanding forms Level 2. At the highest level (3), the understanding of the state of the system and its dynamics can allow them to be able to

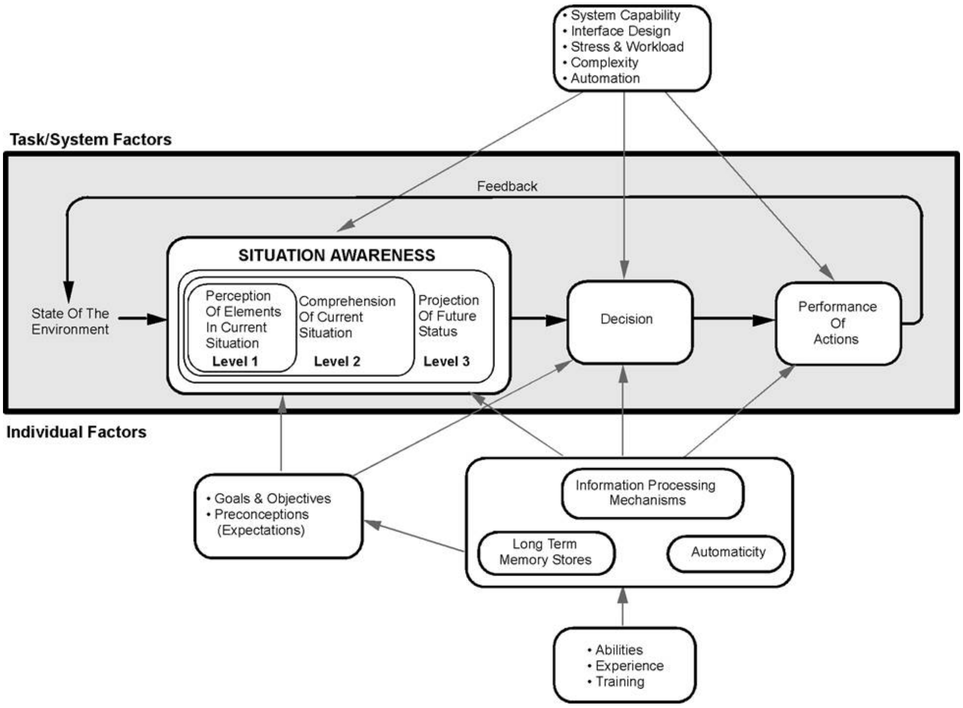


Figure 2.1: Endsley's model of situation awareness adapted from Endsley (1995)

predict its state in the near future (the car in front of me will decelerate and halt in front of the stop line). The constant change of the situation is an important factor in Endsley's concept. Because the situation is dynamic, one task of the operator is to estimate how fast certain information can change and thus influences the possibilities to project future statuses. Accordingly, the operator has to update his situation assessment constantly. Therefore, it is possible to react to changes in the environment and form a new decision . The decision of his action and the performance of action are not part of situation awareness. They are seen as a result of situation awareness. As depicted in Figure 2.1, numerous factors influence the processes postulated by Endsley. On the one hand, individual factors like the operator's goals and expectations and, on the other hand, task/system factors like complexity of the tasks or stress level play a role. On the side of the individual factors, especially long term memory and the effecting expectations play a role for the gathering of SA. Through experience, mental models or schemata are developed that help in recognizing complex driving situations (Krems & Baumann, 2009). These factors can lead to wrong decisions even though the situation assessment is adequate. For example, the operator might not have enough experience, choose a wrong strategy, or the workload is too high.

For the decision making process the operator has to have goals in the environment. Long term goals (i.e., arriving at work) can be broken down

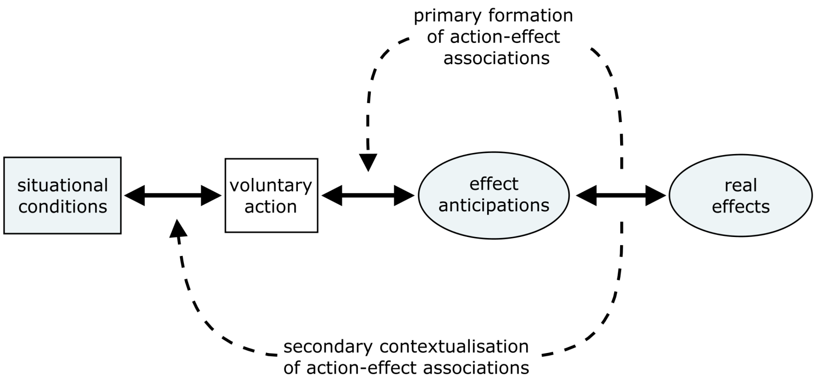


Figure 2.2: Illustration of the ABC framework: The acquisition of anticipative structures (adapted from Hoffmann, 2009)

into situational goals (i.e., following the lead vehicle at a safe distance). How these goals are transferred to behavior and how the behavior control is learned is in the scope of the Anticipative Behavior Control (ABC) Theory (e.g., J. Hoffmann, 1993, 2009). J. Hoffmann (2009) develops the statement "voluntary behavior is primarily determined by anticipations of the sensory effects the behavior produces instead of being determined by the current stimulation." This insight was already made by William James who used the term "ideo-motor principle" to describe that the motor output is determined by an idea of the desired outcome: "An anticipatory image ... of the sensorial consequences of a movement, ... is the only psychic state which introspection lets us discern as the forerunner of our voluntary acts." (James, 1890). And to be voluntary per the definition, the being has to have an idea of the outcome. This it the basis for the Anticipative Behavior Control Theory by J. Hoffmann (1993). The acquisition of anticipative structures is illustrated in Figure 2.2. Intentional or voluntary behavior is triggered by the desired effect (effect anticipation). The desired effect is compared to the actual result (real effects). Throughout repetition a connection is built up between resulting effects of certain behavior. The foresight of the behavior's effect is the anticipation. In the classical ideo-motor theory, the situational context did not play a role. In recent research the view on the context or situation is enhanced (e.g. Kiesel & Hoffmann, 2004; J. Hoffmann & Sebald, 2005; Pfister, Kiesel, & Melcher, 2010). In Figure 2.2 the situation is represented by the left box. Situations in which the action led to the desired effect strengthen the connection between situation and action. If the effect does not match the outcome, the situational conditions are being differentiated more precisely. The ABC theory has direct implications on selective attention. Anticipative behavior control selects the information from the environment that is needed or is learned to be connected to the desired effects respectively for voluntary action. Goals lead to the automatic orienting of

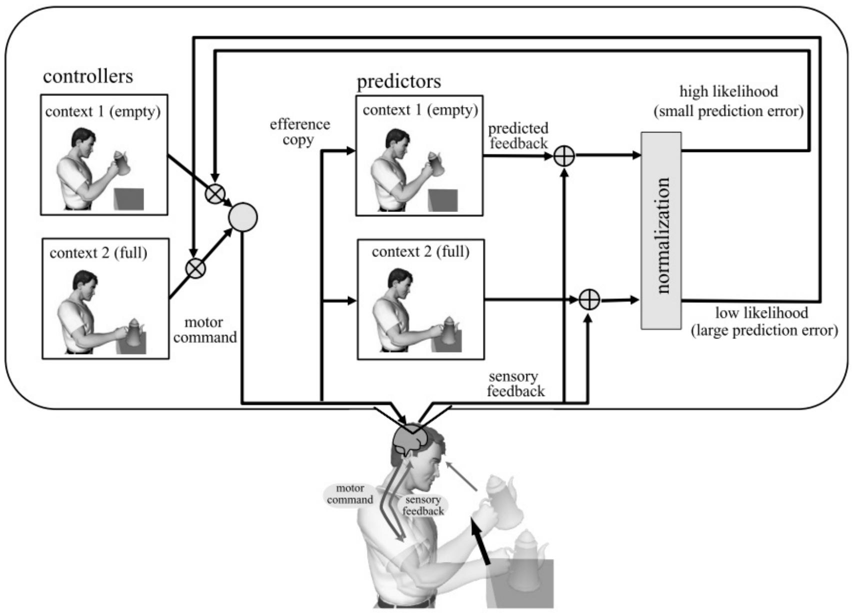


Figure 2.3: The MOSAIC architecture with two contexts (taken from Wolpert et al., 2003)

attention towards goal relevant objects (Vogt, Houwer, Moors, Damme, & Crombez, 2010) and anticipation determines a top-down attention process, in order to acquire the information needed for the intended action and/or effect (e.g. Haazebroek & Hommel, 2009).
How movements are controlled in dynamic environments is missing in the ABC theory. An approach to motor learning, very similar to the ABC model, is the the modular selection and identification for control (MOSAIC) model (Wolpert & Kawato, 1998). The MOSAIC model explains motor learning and control based on multiple pairs of forward (predictor) and inverse (controller) models. The architecture simultaneously learns the multiple inverse models necessary for control as well as how to select the set of inverse models appropriate for a given environment. It combines both feed forward and feedback sensorimotor information so that the controllers can be selected both prior to movement and subsequently during movement. Central to the MOSAIC model is that the object handled can have distinct and changing dynamics. The example of the MOSAIC model in Figure 2.3 is explained by Wolpert, Doya, and Kawato (2003)

> (Shown is a...) schematic of context estimation with just two contexts: that a teapot is empty or full. In this highly simplified example, a module consists of a controller–predictor pair. In this case, two controller–predictor pairs exist: one tuned for a full teapot and one for an empty teapot. The outputs of the con-

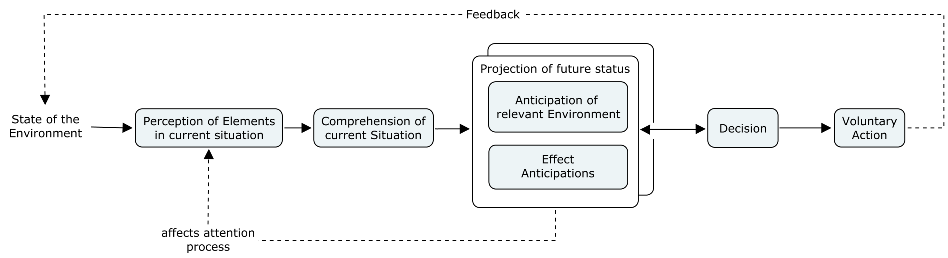


Figure 2.4: Situational Awareness with Anticipative Behavior Control elements

> trollers are weighted by the likelihood that each is appropriate, to determine the final motor command. When this motor command is generated, an efference copy[1] of the motor command is used to simulate, using the two predictors, the sensory consequences under the two possible contexts. The predictions based on an empty teapot suggest that lift-off will take place early compared with a full teapot and that the lift will be higher. These predictions are compared with actual feedback and the errors are normalized to turn them into likelihood or responsibilities. As the teapot is, in fact, empty the sensory feedback matches the predictions of the empty teapot context. This leads to a high likelihood for the empty teapot and a low likelihood for the full teapot. These responsibilities are used to adjust the weightings of the controllers so as to generate motor commands appropriate for an empty teapot. In addition, the responsibilities are used to gate the learning of the predictors and controllers (not shown).

The MOSAIC model allows learning the inverse models to control the movement as well as selecting the inverse model for the certain environment. Because of the multiple controllers and predictors, it offers a possibility of quick changes in the motor control.
In comparison to the Situational Awareness model, the ABC Theory emphasized the anticipation of the effects of the own action more, whereas the SA model deals only with the assessment of dynamic situations but sees decisions and influences of the own actions only as input on the environment. The MOSAIC model gives a framework for how a change in the environment can lead to a quick adaption of behavior. But as ABC theory showed, situation perception and decision making are linked in both directions. To explain the whole idea it is proposed to combine the two. The enhanced model is shown in Figure 2.4.

As the flow is circular, one could start at each position. Here, the Environment (left) will be the starting point. The operator perceives the

[1]Efference copy is an internal copy created with a motor command of its predicted movement and its resulting sensations

elements of the current situation and forms a comprehension of the situation. This step, as in the SA model, is influenced by factors like Abilities and Experience (not shown). As in the example of the MOSAIC model, multiple projections of the situation are possible and are processed in parallel. Driven by the goal of the operator (not shown), the operator makes a decision and hence determines/chooses the controlled anticipation. This anticipation has to include the effect anticipations and anticipations about the environment. Only the joint anticipation of environment and EGO effects can effectively make it possible to act in a dynamic environment. This further means that a constant update of the situation and comparison of the progress of the situation has to be managed. With the complexity of situations, a top-down attention allocation has to be part of the decision to track the relevant objects, and hence influences the perception of elements. Therefore, only a certain set of possible outcomes is predicted. And the action of the operator feeds back to some of the elements and their behavior in the situation. As this process has to be an online assessment, all the elements affect each other.

Despite the focus on the most relevant objects, a holistic situation check from time to time can be part of the SA process. This could be a result from the driver's goal or be part of the strategic behavior (Bernotat, 1970) or knowledge-based behavior (Rasmussen, 1983).

The perception of the current elements in a situation is the foundation for the build up of situational awareness and anticipation. To understand the driver's anticipation and possible mistakes, it is essential to know the human specifics in perceiving the environment. Only if one knows how and what will be perceived by the driver is it possible to explain certain shortcomings in accident prevention. Therefore, the next section will deal with the aspects of perception that are relevant for driving.

2.1.3 Relevant aspects of Perception

To navigate through the environment a three dimensional representation of the surrounding objects is needed. In the setting of driving a car this information is gathered primarily by the visual system. The perception of depth and distance is accomplished though the operation of several perceptual cues. These cues are divided into object-centered cues and observer-centered cues. The object-centered cues also work in a 2D display. Examples are linear perspective, interposition, light and shadow, relative size, and motion parallax. The motion parallax is the effect that near objects have greater relative motion when the observer is moving though a scene. The three observer centered cues are characteristics of the human visual system. The binocular disparity is the difference of the two pictures that the two eyes perceive because the location of the eyes is slightly different. The convergence is the positioning of the two eyeballs in order to focus on an object. Accommo-

dation is a cue provided to the brain by the eye muscles for the strength to adjust the shape of the lens to bring the image into focus on the retina. Work by Eberts and MacMillan (1985, cited in Wickens, 1999) studied the causes of rear-end collisions. They found, in the statistics, that small cars are rear-ended more often than large cars. They hypothesized that because of the cue of relative size the small cars are perceived as further away than they really are. And this leads to a late brake reaction as the anticipation of the collision is wrong. They confirmed this hypothesis in an experiment. In a driving simulator experiment by Fajen and Devaney (2006), participants learned to attune to object size and their own speed (by using global optical flow rate) in order to learn to control collisions.
As someone is moving though space, he has to control his motion through that space: direction, velocity and acceleration. What information does he detect in the environment that allows him to do so? The perception of velocities and acceleration can be divided into perception of self-motion and target motion. One key factor of judging is optical flow. The optical flow is the relative velocity of points across the visual field as one moves through the world. There are two important pieces of information in optical flow to indicate the direction of heading. First, there is the difference of velocities of the objects in the field of view. And second, the expansion point, which is the point of no flow, but where all motions seem to start (Wickens & Hollands, 1999). Optical flow differs for stationary and moving objects. So the observer can detect if an object is moving or not. Only stationary objects give the observer information about his heading.

If one is on a collision course with another object it is also important to deduce the time until impact - the so called "Time To Collision" (TTC). The TTC is a projection of a future state, and hence is a prospect to the section "Anticipation in Driving" (2.1.5). This point will be taken up again in the mentioned section. The parameter time to collision is an objective measure of the criticality of the relative movement of two objects. It is the time remaining until a moving object makes contact with another object, assuming that the object's speed and heading remain the same. The TTC is calculated with the measurements of the distance between two objects (d) and the relative velocity of these objects (V_{rel}).

$$TTC = \frac{d}{V_{rel}} \tag{2.1}$$

TTC can be directly perceived by humans by the rate of change of expansion of an object (or surface) as the observer moves. This characteristic number is referred to as Tau (τ)(Wickens & Hollands, 1999, p.162). Humans can detect object velocities visually by analyzing Tau. The information about the self-motion is integrated into sensing object movement. In a laboratory simulator experiment, the optical flow rate was manipulated and participants systematically over- or underestimated TTCs due to optical flow rate (Gray

& Regan, 2000). However, whether or not humans can perceive object acceleration by target movement is not clear. In one laboratory experiment it was shown that object acceleration could not be correctly verbalized (Dubrowski & Carnahan, 2002). On the other hand, in the same experiment it was shown that humans intercept accelerated objects correctly, but they could not verbalize different accelerations (Dubrowski & Carnahan, 2002). Contrastingly, another experiment revealed that the participants used the current velocity of an object but not the acceleration to calculate a TTC, thus disregarding the acceleration (Benguigui, Ripoll, & Broderick, 2003). This was true for perception as well as action in this experiment.

Humans can perceive their own velocity and that of other objects with different mechanisms. Acceleration is hard to verbalize, but correct reactions to it is possible. As just laid out, the driver has the perceptual abilities to detect the relevant parameters for collision anticipation. A crucial prerequisite of this is that the relevant elements are present.

2.1.4 Attention

In 1890 William James wrote in his textbook *Principles of Psychology*:

> Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called distraction, and Zerstreutheit in German (James, 1890, p.403-404).

But, attention is an umbrella term for a variety of psychological phenomena. However, there is some agreement that attention involves a selection process. Furthermore, it is characterized by a limited capacity for processing information and that this allocation can be intentionally controlled (e.g., Styles, 1997). Attention can be focused volitionally by "top-down" signals derived from task demands. This is what James refers to. But attention can also be grabbed automatically by "bottom-up" signals from salient stimuli (Desdimone & Duncan, 1995). When talking about visual attention the volitional "top-down" mechanism can be thought of as a spotlight. Visual attention can volitionally be located at one spot or object. And this metaphor has to be stretched to features of objects (e.g., color), complete objects, or objects for a certain response (Treisman, 1998). J. Hoffmann and Grosser (1985) also showed that entire objects could pop out when the attentional focus was laid on them. A mixture of top-down and bottom-up processes

is typical for most human behavior like, for example, moving through a dynamic environment. On the top-down side, the attention is allocated at a certain place in the environment or a certain object / road user. But, of course, the bottom-up process also plays an important role in safe driving. Bottom-up processes take place when a new object occurs or a salient stimulus pops out without volitional attention. A typical visual example could be the flashing light of an emergency ambulance. Typically, an orienting reflex follows and aligns the attention to the stimulus.
On the other hand, the sensorial perception of a stimulus is not identical with the conscious perception of it. For a conscious perception of a stimulus, attention is necessary to lead to cognitive processing. As a result, lack of perception happens and, in traffic, can lead to crashes. Especially, intersection accidents are affected by this problem. 69-80% of intersection accidents can be traced back to a lack of perception of the involved vehicles (Simons, 2000). This phenomenon is called "looked-but-failed-to-see" or "inattentional blindness" (Simons, 2000) and is described as "failure to notice salient and distinct objects [...] something that is potentially relevant but not expected". Herslund and Jörgensen (2003) see the cause in the looked-but-failed-to-see crashes as mistakes of search strategy and cognitive processing. There are indications that some kind of top-down attention is always needed to process a stimulus. That seems to be true even in the bottom-up situations.

Although this will not be further elaborated, it has to be mentioned that attention is influenced by several moderator factors, such as mental workload, fatigue, habit, and age.

In this thesis, it is of importance to define what an attentive driver is. It seems there is agreement that a driver who is only involved in activities critical for safe driving is an attentive driver. This includes cognitive as well as behavioral involvement. Everything else on the topic of "attentive driver" is under discussion. As in a lot of applied research, only overt behavior can be analyzed, with some practical assumptions established for some researchers: A driver who has his hand on the steering wheel (or the gear shift) and is looking towards the forward scene is considered as being attentive. Also, a driver who is systematically scanning his/her environment (including the instruments) is an attentive driver (Klauer et al., 2006). On the other hand, the subject is often discussed from the opposite side of *inattention* (see e.g. Regan, Hallett, & Gordon, 2011; Stutts et al., 2001; Trick, Enns, Mills, & Vavrik, 2004). The assumptions are often not compatible with the ones expounded so far. Regan et al. (2011) provide a taxonomy of driver inattention which is shown in a shortened version in Table 2.1. The taxonomy from Regan et al. (2011) and the definition byKlauer et al. (2006) are mutually exclusive. A driver who is scanning his environment (attentive, according to Klauer) can, for example, at the same time misprioritize his

Restricted attention – "Insufficient or no attention to activities critical for safe driving brought about by something that physically prevents (due to biological factors) the driver from detecting (and hence from attending to) information critical for safe driving." E.g., change blindness; eyes closed or closing due to fatigue; eyes wide open when fatigued and "looks but cannot see."
Misprioritized attention – "Insufficient or no attention to activities critical for safe driving brought about by the driver focusing attention on one aspect of driving to the exclusion of another, which is more critical for safe driving." E.g., the driver does a shoulder check when merging and, in doing so, fails to see a car in front stopping and hits it.
Neglected attention – "Insufficient or no attention to activities critical for safe driving brought about by the driver neglecting to attend to activities critical for safe driving." E.g., fails to look for trains at level crossing and drives straight though without looking because trains are rarely or never seen; neglects to scan for motorcycles when turning left at an intersection because they are less expected than cars and trucks.
Cursory attention – "Insufficient or no attention to activities critical for safe driving brought about by the driver giving cursory or hurried attention to activities critical for safe driving." E.g., driver performs a hurried shoulder check when merging and collides with an unseen vehicle when merging on a freeway; driver fails to perform a complete head check when backing out of a car park.
Diverted attention (i.e., **distraction**) – "The diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving." The competing activity can be driving-related or non-driving related.

Table 2.1: Driver Inattention Taxonomy (adapted from Regan et al., 2011)

attention (inattentive, according to Regan).
In this thesis, the term *attention* will be used in the way Klauer et al. (2006) has proposed it. For example, a driver who misprioritized his attention will still be considered attentive. A driver who engaged in a secondary task (diverted attention) will be considered inattentive or distracted.

2.1.5 Anticipation in Driving

Is there enough time to fulfill an overtaking maneuver before a curve? Will the gap between two cars shrink and is it safe to cut in? These are example questions that a driver has to answer in everyday driving. To be able to do that the driver has to anticipate his own state, the state of other road users as well as the course of the road. Hence, as already pointed out, anticipation is a prerequisite for moving/driving in a dynamic environment. Looking at the examples, anticipation is a part of "maneuvering" in the stage models of driving (e.g. Michon, 1985). The information generated by anticipation is relevant for this level. The time perspective of the "maneuvering" level is thought to be seconds. Several experiments suggest a timing of some

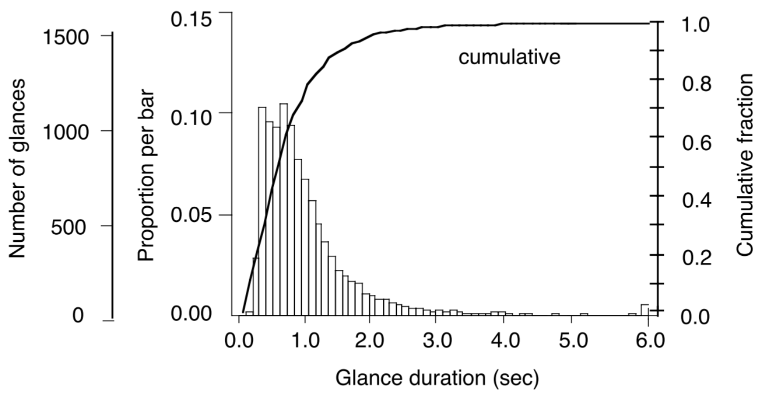


Figure 2.5: Histogram of all glances from Hada (1994) - Experiment 1

seconds for anticipation. Also, cues from the environment are taken to plan the next maneuvers. Humans are quite good at extrapolating linear trends. But they are biased when extrapolating in a linear manner, even when the development so far has not been linear (Wickens & Hollands, 1999).

The task of gathering information from the environment is primarily visual in driving. As a basis for good situational awareness and anticipation, the driver has to visually scan the environment (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). As explained, the attention is allocated top-down most of the time and driven by the goals set and anticipations made. Attention is focused to the areas or objects that are relevant for planning further actions. For example, Underwood et al. (2003) showed that drivers focused on the road ahead more than any other part of the scene. They also found that whenever the drivers' attention is taken away from the road it is then invariably refixated at the point that delivers maximum preview. And, for example, mirror inspections increase on two-lane roadways. This was significantly more for experienced drivers in relation to novice drivers. Mortimer and Jorgenson (1975) report that 80% of all visual fixations at a velocity of 90km/h are about 75m in front of the car. This resembles a time gap of 3s. When approaching a curve drivers look at the tangent point to judge the curvature. This is the area that provides the best information to the driver on how to steer through the curve. In a real road experiment, U.S. participants where asked to look away from the road as long as they think it is safe (Hada, 1994). The median for the glance duration off the road is at 0.7s, while the 95-percentile is 2.2s (see also Chapter 2.5). The participants drove on an Expressway, a rural road and on suburban streets. The drivers chose the longest glance durations for the Expressway and the shortest for the suburban area.

In an overview report on driver in-vehicle distraction and glance behavior, P. Green (1999) summarizes the longest mean times for a single glance for conventional instrument panel functions (e.g., speedometer, radio, clock) ranged from 1.2 to 1.85s, depending on the study and function. He also states that "drivers loath to go for more than 2 seconds without information from the road." (P. Green, 1999, page 55). The reported times fit well to the maneuver level and shows that drivers have the urge to get constant visual updates to plan their behavior.

Hulst (1999) investigated the anticipatory behavior of automotive drivers. They staged different traffic scenarios in a driving simulator. Some scenarios had cues that the lead vehicle would brake (e.g., obvious crossing traffic) and some had no cues. The expected decelerations were presumably detected faster than unexpected decelerations. Drivers adjusted the timing of their responses very well to the level of deceleration of the lead car. If cues in the environment indicated that the lead car was likely to decelerate, drivers reacted faster. Moreover, drivers increased their headway before the lead car actually started to decelerate, which can be considered an anticipatory response. In general this study shows that anticipation allows drivers to maintain their preferred headway and control time pressure in driving. In a similar experiment, it was shown that the use of a turn signal by the lead vehicle before braking at an intersection is also used as a cue and helps the driver to maintain a safe headway (Muhrer & Vollrath, 2010).
Velichkovsky, Dornhoefer, Kopf, Helmert, and Joos (2002) conducted a study about the phenomenon of Change Blindness. Change Blindness is the name for the phenomenon that people do not realize changes in a given scene. Mostly, experiments work with suddenly appearing objects or vanishing objects. The participants in this experiment looked at video stills of traffic situations. After an occlusion a change was made in the picture. The change could either be relevant or irrelevant for the driving situation the picture was taken in. The detection of relevant changes was both more likely and faster than that of irrelevant ones. This result supports the idea of goal directed attention.

Rauch (2009) developed a method of measuring Situational Awareness while driving. Participants were asked to perform a side task while driving when prompted. The prompt to perform the side task was given in different driving situations. The situations differed in the quality of cues to anticipate conflicting traffic behavior in the future. If cues for a soon to become complicated driving situation were missing, participants performed the side task more often and longer. Similarly, the likelihood was higher that participants started with the side task the further away they were from a curve. Generally, Rauch (2009) states that if possible, drivers extract cues and anticipate complex driving situations, which leads, amongst other measures, to fewer executions of the side task.

A very direct aspect of anticipation in driving is the already mentioned Time to Collision (TTC). The TTC might mathematically represent what

collision anticipation is doing. It is essential to remember that the TTC is calculated under the current conditions.
The perceived TTC under quasi-realistic driving conditions was tested by Kiefer, Flannagan, and Jerome (2006). A total of 51 participants (aged 20-70 years) experienced approaches to a lead vehicle. The subject's car drove at a constant speed (48, 72, and 96 km/h). The lead vehicle was slower and V_{rel} resulted in 16, 24, 32, and 48 km/h. The driver's vision was occluded by shutter glasses at either 3.6 or 5.6s TTC during an in-lane approach to a lead vehicle. Drivers provided TTC estimates by pressing a button the instant they felt that they would have collided with the vehicle ahead. For half of the trials for each participant, the shutter glasses were open until the 3.6 or 5.6s TTC. On the other half, vision was occluded when the target speed was reached and just opened for 1s before the respective closing TTC. The results reveal that the TTCs were underestimated under all conditions. The actual TTC increased as driver speed decreased and as relative speed increased, but were still not overestimated. The ratios of (perceived TTC/actual TTC) were largely unaffected by age, gender, actual TTC and viewing time (1s vs. continuous). The estimations for these relatively short TTCs have little variance. The ratios of perceived TTC/actual TTC varied between 0.45 and 0.65.
Schmidt, Khanafer, and Balzer (2009) tested driver urgency assessments under similar conditions as Kiefer et al. (2006), but did not use shutter glasses. The participants (N=8) were approaching a lead vehicle at a constant speed (both cars cruise controlled) and had to indicate when they first felt that the situation was dangerous by the push of a button, then brake at the last second. The host vehicle drove at 80, 100, and 130km/h, while the lead vehicle realized relative speeds of 50, 30, and 10 km/h. Regardless of the host vehicle's speed, the “danger zone” started at approximately a TTC of 3s with relative speeds of 50 and 30 km/h. With 10 km/h relative speed, the values were a little higher.

As shown with the cited experiments, behavior that facilitates anticipation is part of everyday driving and essential for this task. Experiments showed that expectations are built up from cues from the environment like a turn signal, or the general course of the road, and lead to different behavior in drivers (Hulst, 1999; Muhrer & Vollrath, 2010; Rauch, 2009). Advantageous for traffic safety is the insight that the assessment of the TTC is conservative and helps to avoid collisions.

2.1.6 Relevant Measures of Driver Behavior

Anticipation and Situation Awareness affect the driver behavior. Some measures in the area of collision avoidance have already been part of this work. This section will deliberately introduce objective measures often used to de-

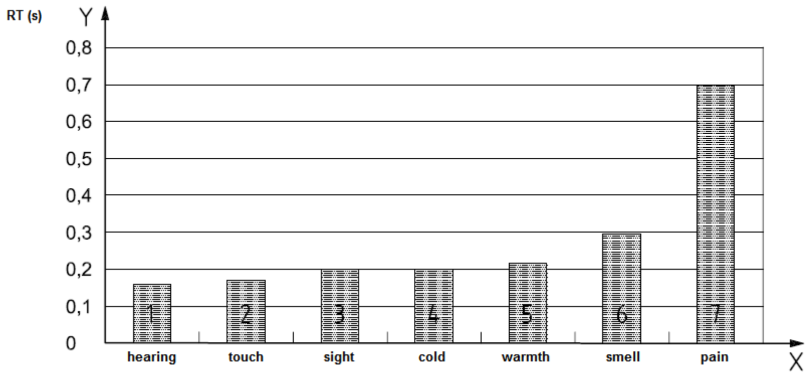


Figure 2.6: Reaction times dependent on sensorial modality (according to Woodson, 1981 cited in ISO, 2005)

scribe driver behavior and driver decisions. This knowledge will later be used to design and analyze the experiments of this work.

Driver (Brake) Reaction Time

The most frequently used behavioral measure is reaction time (RT). Independent of the critical behavior measured, the point in time when it is initiated enables an estimation of the driver's situation assessment. For example, one usually assumes that avoidance behavior is initiated immediately when a hazard is detected. Exemplary research questions are: How fast do drivers react in traffic situations without assistance systems? And, if a driver could be warned of a critical situation - how long does it take him to make a decision, react and finally stop? A driver has two alternatives when trying to avoid or mitigate a forward collision: The driver can brake and / or steer around the obstacle.

When talking about reaction times, it is expedient to keep in mind there is nothing like *the* reaction time. It varies inter individual as well as intra individual due to different situations. This section will talk about the various factors influencing reaction times. Special emphasis is put on conditions that are relevant for brake reactions.

What are the expected reaction times? Simple reaction times (RT) in laboratory settings have been found to be roughly 130ms for auditory and 170ms for visual stimuli (Wickens & Hollands, 1999, p. 339). For an overview, some examples of RT for different human senses are giving in 2.6.

Simple RT decreases with increases in intensity of the stimulus to an asymptotic value depending on the special case (e.g., Piéron, 1913; Kohfeld, 1971; Jaskowski, Rybarczyk, & Jaroszyk, 1994; Miller, Franz, & Ulrich, 1999). This effect could be shown for several stimulus modalities. It is thought to be a two-stage effect. First, the aggregation of stimulus evidence depends on the intensity of the stimulus, as in signal detection theory. Second, higher

intensity stimuli lead to a higher arousal in the recipient which leads to a faster motor response.
The number of response choices is another moderating factor. It has been found that one choice adds an average perception-response time of 200ms. On average, two choices increase the response time by 350ms. Additional choices added 50ms each, up to a maximum of nine, at an average of 650ms. Simple Brake RT in cars following a sound or a visual stimulus have been found to be 750ms for the 85-percentile of the participants. When participants were surprised by a suddenly appearing hazard, 95% of them had responded by 1.6s. When they knew about the hazard, but there was a time uncertainty regarding when the hazard appeared, 95% of the responses were 1.15s or less. The shortest Break RT was about 0.8s for 95% of informed participants (Olson, 2001). Usually Brake RT is divided into two parts:

1. initial RT (time until the foot begins to decrease pressure on the accelerator pedal), and

2. movement time (time for foot movement from initial accelerator release until initial brake pedal movement)

For the complete process of brake reaction another component plays a role. The deceleration build-up time is a vehicle and environment dependent factor that alters the brake reaction of the car.
Burckhardt (1985) worked out a detailed time sequence of driver brake RT sections for the German jurisdiction. The data basis is an experiment with 41 participants (7 female, 34 male) aged from 18 to 58 years. The participants followed a confederate car. They should apply the brakes as fast as possible when they recognized the illumination of the brake lights of the confederate car. For each participant, about 100 break scenarios were recorded. The original raw data was statistically reanalyzed by Hugemann (2002). These results are referred to in Table 2.2. The entire RT is divided into five sections: Gaze shift (if focus is < 5), saccadic correction (for > 5), mental processing , foot movement time, and deceleration build-up time. This results in a basic reaction time of 1.03s, when the driver is looking in the direction of the breaking lead vehicle for the 98%-percentile. In Germany, due to this result, this reaction time is called the "Schrecksekunde" (panic second).

It is of high interest how long drivers need to perceive an unexpected hazard and respond to it. For example, the American Association of State Highway and Transportation Officials (AASHTO) formulated guidelines for driver perception and response for several conditions. The Stopping Sight Distance (SSD) is an example of that. Sight distance, in the context of road design, is how far a road user can see before the line of sight is blocked. Stopping sight distance is the distance traveled while the vehicle driver perceives a situation requiring a stop, realizes that stopping is necessary, applies the brake, and comes to a stop. It is used to define minimum radii for curves and

	2%	50%	98%
Gaze shift < 5°	0.32 s	0.48 s	0.55 s
Saccadic correction (for > 5°)	0.09 s	0.13 s	0.15 s
Mental processing	0.22 s	0.45 s	0.58 s
Foot moving time	0.15 s	0.19 s	0.21 s
Deceleration build-up time	0.17 s	0.22 s	0.24 s
Basic reaction time	0.54 s	0.86 s	1.03 s
+ gaze shift < 5°	0.86 s	1.34 s	1.58 s
+ gaze shift > 5°	0.95 s	1.47 s	1.73 s

Table 2.2: Sequence of sections in driver Brake Reaction Time

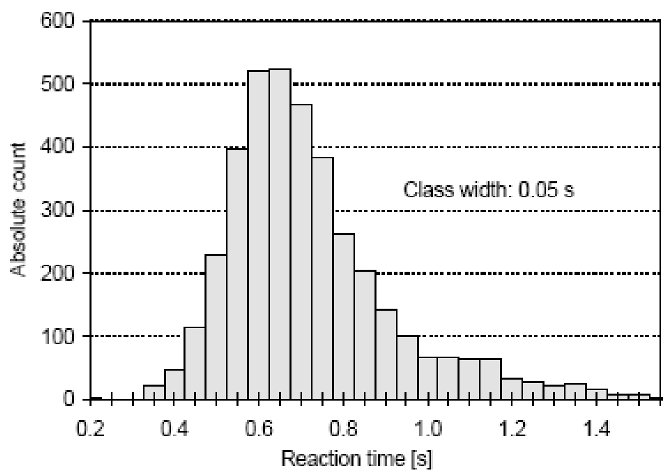


Figure 2.7: Example of reaction time distribution (Burckhardt, 1985)

hill crests to prevent hazards appearing too suddenly. The driver reaction time considered in calculating the SSD is set at 2.5s (Olson, 2001).
In a meta analysis, M. Green (2000) scanned 41 studies concerning brake reaction time (BRT). One major outcome of this analysis was that the method of the study itself impacts the BRT the most. The different study types that influence the BRT are the following: Under sound conditions, which are low uncertainty, intense visual, foveally viewed signal, but with no recent practice, the best expected BRT is about 0.7 to 0.75s. That consists of about 0.50 to 0.55s perception time and 0.20s movement time. Without instruction, RT to "normal" stimuli as brake lights are 1.25s including a movement time of 0.3s. Realistic data reveals a BRT of 1.5s when the driver does not expect any hazard. Age effects are small in relation to other factors and are easily lost in the noise. The results for gender differences are equivocal.
With regard to urgency, results suggest that BRT is a U-shaped function. That means the RT "(...)is decreasing with greater urgency but then paradoxically becoming very long when time-to-collision is short"(M. Green, 2000, p.221). This is more likely to happen when there is the opportunity for alternative responses. In general, RT goes up when the driver is involved in a high cognitive workload task (e.g., using a mobile phone). Some studies, in contrast, reveal no difference in RT between high and low workload. The explanation given by M. Green (2000) is, that these drivers might be aware of the dangerous situation and compensate by being more attentive on the driving task. If the study setup impacts the BRT, how valid are driving simulator studies in relation to collision avoidance BRT? McGehee, Mazzae, and Baldwin (2000) conducted a simulator study and a follow-up test track study to answer this question. The study was designed so that an unexpected intersection incursion scenario could be safely implemented on a test track. In both studies an obstacle occurred unexpectedly on the road. On test track a, a full size foam core photograph mock-up was moved about 2m in the participants' way, when they passed over a tape switch on the pavement. Comparisons were made between primary reaction times across both simulator and test track studies. One drawback is that the participants on the test track study had to accomplish a secondary task whereas in the simulator study they did not. There is no significant difference for the total BRT and the time to initial steering. Only the initial accelerator release time was faster in the simulator than on the test track (see Table 2.3).

It can be put on record that Brake Reaction Times vary heavily inter-individually and depend on the test setup. Nonetheless, it can be noted that the fastest BRTs can be expected to be around 0.7s including 0.2s movement time. When participants do not expect an urgent braking reaction, BRTs usually lie between 1 and 2s.

	Simulator	Test track
Initial Accel. Release	0.96s	1.28s
	SD 0.21	SD 0.29
Total Brake RT (to max brake)	2.2s	2.3s
	SD 0.44	SD 0.46
Time to Initial Steering	1.64s	1.67s
	SD 0.49	SD 0.46

Table 2.3: Mean Break RT and standard deviation for simulator and test track

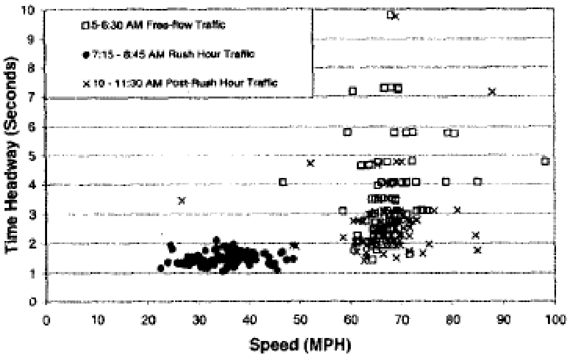


Figure 2.8: Time-headway as a function of speed (Ayres et al., 2001)

Time Headway

The headway between vehicles is the amount of time that elapses between two vehicles passing the same point and traveling in the same direction. Time Headway can be seen as an uncertainty buffer or safety margin for lack in anticipation. It can be assumed that drivers accept shorter headways when they anticipate a constant velocity of the vehicle(s) in front of them. German jurisdiction demands a headway of at least 1.8s for car following. When the headway falls below 0.9s the driver incurs a penalty. The typical safety rule in the USA defines a 3s headway as adequate (e.g. Schwarzenegger, Bonner, & Valverde, 2007).

T. Ayres, Li, Schleuning, and Young (2001) recorded realistic traffic flow data for December 1999 for a section of highway 101 south of San Francisco. They quantified the parameters of speed and headway to find drivers' preferred time-headway in real-world driving. The results, as presented in Fig. 2.8, show a minimal headway of 1s. In free-flow traffic, drivers choose a constant speed and the headway ranges from 1s to values based on the volume of traffic. In rush hour traffic the speed is between 20 and 50 mph (32 and 80 km/h) and time-headway between 1 and 2s.

Ervin et al. (2005) conducted a field operational test (FOT) with 69 participants. Each participant drove a car equipped with measurement systems for about two months. The goal of the FOT was to examine the suitability of an Automotive Collision Avoidance System (ACAS) from the perspectives

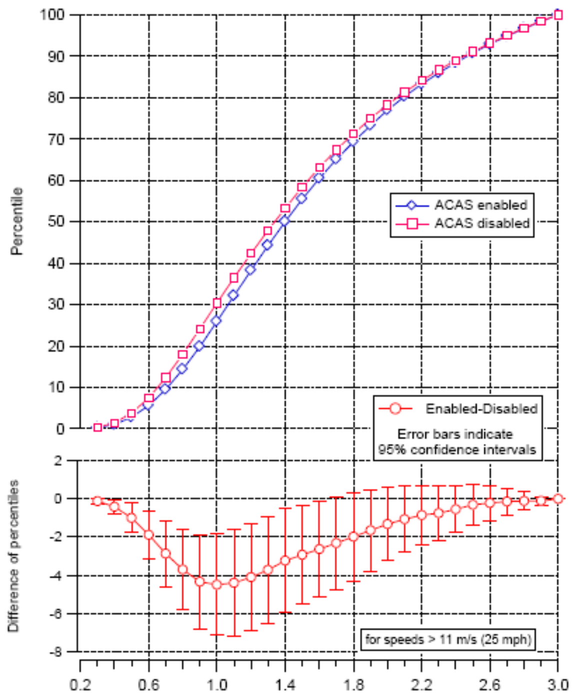


Figure 2.9: Means and differences of the cumulative histograms of headway time margin while following for driving with ACAS disabled and ACAS enabled in ACAS FOT (Ervin et al., 2005)

of both driving safety and driver acceptance. The ACAS system included both a forward crash warning (FCW) system and an Adaptive Cruise Control (ACC) system. Time-headway was recorded among other parameters. Figure 2.9 shows the headways while following for driving with ACAS disabled and ACAS enabled with $V \geq 40km/h$. Headways larger than 3s were excluded from the analysis. Regarding the data with ACAS disabled, the shortest headway recorded is 0.3s. The median of this distribution is about 1.35s. The lower limit of the interquartile range (IQR) is 0.9s, the upper limit is 1.9s. When the ACAS was enabled the headway increased a little, especially around the median.

Neubert, Santen, Schadschneider, and Schreckenberg (1999) analyzed traffic data recorded by inductive loops on a German highway. The data was collected after 10 days, when a total number of more than 500,000 vehicles passed, nearly 16% of them being trucks and truck trailers. The authors classified traffic density in three parts: free-flow, synchronized, and stop-and-go traffic. The free-flow distribution is dominated by a two peak structure (see top panel of Fig. 2.10). The global maximum is at a headway time of 0.8s. The second peak emerges at 1.8s headway, which Neubert et al. (1999) interpret as the "normal" driving behavior. Surprisingly, the first peak is not

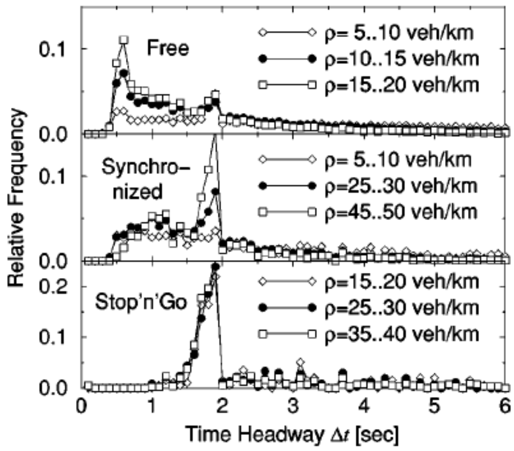


Figure 2.10: Time headway distribution for different density regimes (Neubert et al., 1999)

present in more congested traffic. Only the 1.8s peak emerges again. In this analysis, every fourth driver falls below a 1s threshold. The probability for that rises when it is a free-flow situation, especially with a 10 to 20 vehicles per kilometer congestion. This result can be explained with tailgaiting behavior. Tailgaiting leads to very short headway times.

Resuming these three sets of data, one can note that on highways American and German drivers spend most of the time following a car in the range of 1 to 2s headway time. German drivers tend to drive with shorter time headways than American. The counter intuitive result of short headways in free-flow traffic and longer distances in congested traffic can be seen under the light of anticipation. In congested traffic drivers expect sudden braking maneuvers by the lead vehicle. As a result, the drivers retain a longer distance between vehicles. In free-flow traffic the probability of an unexpected braking maneuver is low and the drivers might anticipate the lead vehicle to show constant movement characteristics. Hence the drivers show short following behavior.

Last Second Braking

Braking behavior can tell a lot about the driver's anticipations regarding the spatial relationship of their car and another vehicle. It can be assumed that drivers have a minimum TTC (and minimum headway) that they accept (Schmidt et al., 2009). Hence the initiation of braking shows that drivers anticipate a dangerous state or even a collision. Objective measures like, for example, TTC at initiation, brake pedal pressure and demanded deceleration, refine the picture of the driver's situation assessment. The following experiments show research on last second braking behavior. The approach

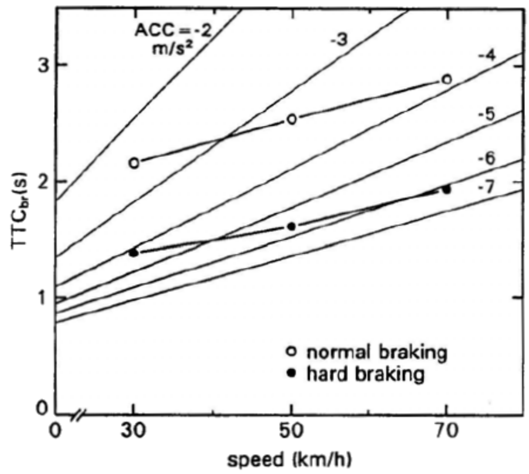


Figure 2.11: TTC_{br} as a function of speed and instruction (Horst, 1990)

was primarily to instruct the participants to react in this way under controlled conditions. The results can be taken to assess braking behavior from real live results.
To gain knowledge about a driver's braking behavior without an ACAS, Horst (1990) conducted an experiment on a test track. Twelve subjects drove an equipped test vehicle towards a stationary Styrofoam object simulating the rear end of a small passenger car. They received one of the following braking instructions (Horst, 1990, p.137):

1. start hard braking (but without locking the wheels) at the latest moment you think you are able to stop in front of the object, or,

2. start normal braking at the latest moment you think you can stop safely in front of the object.

Subjects had to avoid both hitting the object and stopping much too early. They approached with three different speeds: 30, 50, and 70 km/h. And there were 3 occlusion conditions: no occlusion, 25Hz occlusion (10ms open, 40ms closed) and 5Hz occlusion (10ms open, 200ms closed). Every participant fulfilled each condition combination three times. The central dependent variable was the TTC at the onset of braking (TTC_{br}). Data analysis revealed, that the TTC_{br} depends mainly on the instruction and the speed driven (see Figure 2.11). It is not a function of constant deceleration as indicated by the fan lines in the same figure. This was proposed earlier in the work to be a reasonable factor. The participants control the braking process in such a way that TTC reaches a minimum of about 1.1s. This is independent of speed or braking instruction. "This constancy of TTC_{min} over both braking instruction and speed suggests that drivers make use of a kind of a safety margin one don't like to exceed" (Horst, 1990, p.147).

Figure 2.12: Test procedure in CAMP (Kiefer et. al, 1999)

Kiefer et al. (1999) used a similar test setup for their baseline experiment. The test procedure differed in two major ways: no occlusion was implemented and the lead vehicle's movement was varied. It was either stopped or moving at the same speed as the subject's vehicle and then decelerated with a certain intensity. The 36 (18 female, 18 male) participants were instructed either to brake "normal", "comfortable hard" or "hard" in the last second to avoid a crash. The participants had no specific instruction about locking the wheels. The instructed speeds to maintain were 30, 45, or 60 mph (approx. 48, 72, or 97 km/h). The lead vehicle braked with either 0.15, 0.28, or 0.39g.

The participants showed an average deceleration in the normal braking instruction behavior that ranged from 0.2g to 0.4g, whereas in the hard braking instruction the values ranged from approx. 0.26g to 0.54g. The calculation of the average deceleration started at braking onset and ended with the standstill of the vehicle. The peak decelerations were much higher. The average peak deceleration of the subject vehicle when the lead vehicle braked with 0.39g was 0.55 to 0.60g for normal braking and 0.85 to 0.90g for hard braking. The more braking trials the subjects completed the harder they braked. The participants showed almost the same reactions for comfortable hard and hard braking instructions. It seems like subjects can not differentiate between these two instructions. The average minimum range increased with subject vehicle speed. For all braking instructions, on average, the minimum was 3 - 4m when the lead vehicle braked with 0.39g. For a stationary object, the minimum zone ranged from 5 - 6m. Hence, participants added a safety margin to the instruction of braking in the last second. The data of the average braking onset TTC are displayed in Fig. 2.13. The braking onset TTC is dependent on the subject's speed, the lead vehicle's braking, and braking instruction. For the hard braking instruction the TTC varies between 1.8 and 4.2s. Kiefer et al. (1999) and Horst (1990) produce comparable data as shown in Figures 2.11 and 2.13. The 70km/h in Horst's and 45mph conditions for stationary objects in Kiefer's study are comparable. Horst's subjects start braking at about 2.7s TTC and Kiefer's at about 4.7s

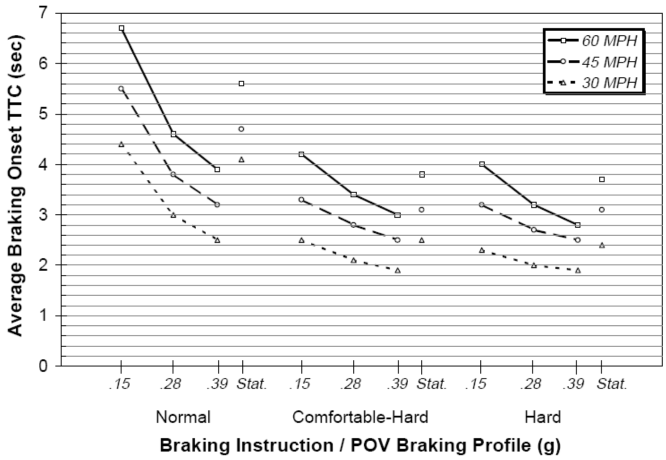


Figure 2.13: Average TTC at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition (Kiefer et al., 1999)

TTC for the normal braking instruction. For the hard braking instruction, Horst's drivers start braking at about 1.5s and Kiefer's at about 3.1s TTC. Kiefer et al. (1999) explain these differences with the experimental settings. They say that in the Horst study the threat was not realistic enough and therefore the Horst study induced later braking behavior. With a more realistic threat, as used with the surrogate target vehicle used in their study, the results are closer to natural behavior.

In a follow-up study, Kiefer, LeBlanc, and Flannagan (2005) used a similar experimental design as in the 1999 CAMP study with 72 participants. The approach of the study was to develop a model of driver brake timing. The main parameter for that approach is the inverse of the TTC (TTC^{-1} or $\Delta V/range$). Kiefer et al. (2005, p. 300 et seq.) argue for TTC^{-1} as the important measure with three points:

> "Inverse TTC is of importance for a number of reasons. First, inverse TTC corresponds to the angular speed of the approaching object divided by its angular size, and hence, is directly tied to the visual looming properties of the lead vehicle (Lee, 1976; Summala et al., 1998). As the driver approaches a distant lead vehicle traveling at a constant speed, the visual angle subtended by this vehicle ahead will steadily increase prior to undergoing a rapid expansion prior to a collision (Groeger, 2000). Second, the inverse TTC measure appears as a term in the time derivative of required deceleration. Third, the Evans and Rothery (1974) in-traffic study found inverse TTC to be a robust measure for describing driver's judgments of whether the spacing to the lead vehicle was closing or opening under near threshold, relative speed conditions."

The analysis results in the development of three different equations for the predicted inverse TTC at braking onset. One for each lead vehicle behavior: stationary, moving, and decelerating. The equations are as follows: D is the distance to preceding vehicle.
If lead vehicle is moving and not braking:

$$x = -6.092 + 12.584 \cdot (\Delta V/D) + 0.0534 \cdot (V_{ego}\, in\, mph) \tag{2.2}$$

If lead vehicle is moving and braking:

$$x = -6.092 + 18.816 \cdot (\Delta V/D) + 0.0534 \cdot (V_{ego}\, in\, mph) \tag{2.3}$$

If lead vehicle is stationary:

$$x = -9.073 + 24.225 \cdot (\Delta V/D) + 0.0534 \cdot (V_{ego}\, in\, mph) \tag{2.4}$$

Lee, Hoffman, Brown, and McGehee (2002) conducted a simulator study in a high-fidelity 6-DOF driving simulator. They replicated the situations by the CAMP project (Kiefer et al., 2005) in the simulator to test comparability of test track and simulator data. They only instructed “normal” and “hard” braking situations. The results for the Brake Onset Range are shown in Figure 2.14. This figure shows that this data is almost identical for the low speed condition. At 60 mph the brake onset distance is quite comparable but the participants maintained a greater safety margin on the test track. Further comparisons showed that the most prominent differences between the simulator and the test track were that drivers in the simulator were less affected by the braking instructions and decelerated more abruptly. Lee, Hoffman, et al. (2002) assume “Possible reasons for these differences include limited visual and vestibular cues in the simulator, and a combination of extended practice and a somewhat artificial lead vehicle on the test track.” This study shows that at low speeds the last second braking instruction is possible to test in a driving simulator. This is especially true for the hard braking trials.

2.1.7 Short summary: Driving and Collision Avoidance

For the task of driving, all channels of perception are needed. For the representation of the traffic situation, visual perception is especially important. Of course, downsides of human visual perception are also relevant for driving. For example, small objects are thought to be further away than large ones and therefore more prone to be run into. The human estimation of velocity of moving objects is good, whereas the assessment of object acceleration is not as reliable. But this is essential for the avoidance of crashes. Fortunately, TTCs are usually underestimated. The top-down allocation of the driver’s attention is a common case in driving. Usually, experienced drivers

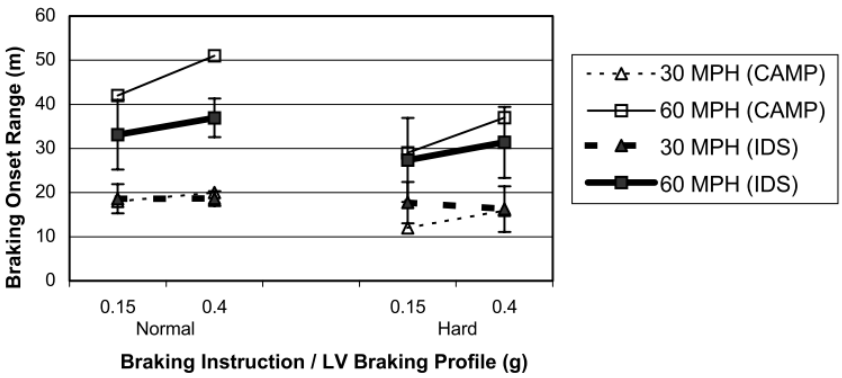


Figure 2.14: Brake Onset Range: Comparison of CAMP and IDS (Simulator) data (Lee et al., 2002)

follow a heuristic approach and are able to gain good situational awareness to build their decisions on. The anticipation plays a major role in this context. Nevertheless, bottom-up attention processes are needed just as well for recognizing unexpected, suddenly appearing objects. Anyhow, phenomenon like the "inattentional blindness" exist.
Decision making has been studied – and will be in this thesis – with the measurement of reaction time. It is important to know that RT decreases with the intensity of the eliciting stimulus and increases with the number of choices for the correct response. Brake Reaction Times are split into two phases: the initial RT and the movement time. The shortest laboratory BRT can be expected to be around 750 ms for the 85 percentile. In real traffic, BRT can be expected to be around 1-2 s.
The time headway measured on real roads shows that drivers usually maintain a time of between 1 and 2s. When drivers have to brake to avoid a collision, the beginning of braking depends on the behavior of the lead vehicle. Is it stopped, moving constantly, or braking? If this is known, drivers react comparably. They never fall below a TTC of 1.1s if they are alert. The last second braking behavior is comparable for real car and simulator experiments when hard braking is considered.
The knowledge built up in this section will be used to design the experiments later in this thesis – to use the right dependent variables and program the scenarios.

2.2 Warnings

In the process of an evolving threat, crash avoidance systems try to support the driver by warning him of an imminent collision if no countermeasures are taken. But before coming to Advanced Driver Assistance Systems (ADAS), this thesis will look at the field of warnings from a general standpoint. Warnings have been studied for a long time and valuable insights shall not be lost. A generic definition of the term Warning is given in T. J. Ayres et al. (1994):

> *A warning is* (...) information about a possible negative consequence – a message that something undesirable may occur to someone or something as a result of taking (or failing to take) some action.

Accepting this definition, all warnings, instructions and rules that include information about negative consequences under certain circumstances induced by the user are warnings. Referring to Semiotics (i.e., the study of signs and symbols), signs can be distinguished in natural and artificial signs (Eco, 1977). Natural signs are not intentional, but can be interpreted. Artificial signs need to be intentional communication. As warnings are a special kind of sign, they can be distinguished in that way. An example of a natural warning would be the black-and-yellow markings of a yellow jacket. Artificial warnings are, for example, the snarl of a dog or a traffic sign indicating a railroad crossing.

The International Organization for Standardization (ISO) (2005) defines a warning from an applied standpoint: "A warning is rated information. A good warning should include:

- an element which attracts attention
- a reason for the warning
- the consequences if the warning is not observed
- instructions for actions."(ISO, 2005)

No system is perfect. Thus warnings sent out by a dynamic system are not always correct. The same text of the ISO defines different types of false warnings:

- time-dependent false warnings: too early, too late
- logical false warning: no warning in critical situation and vice versa
- qualitative false warning: too many, too few, too strong, too weak.

False warnings have an important impact on the interaction of a user and the warning system. In a later part of the work this will be fleshed out (cf. sec.2.2.4).

Figure 2.15: Three warning signs (curvy road, smoking kills and noxious)

2.2.1 Physical attributes

Warnings come in various physical forms or modalities. All human senses are used to perceive stimuli as warnings. Even the olfactory system senses foul nourishment and this is interpreted as a warning not to eat that food. In the terminology of Semiotics, this would be a natural warning. But there are artificial olfactory warnings: Some noxious but odorless substances are enriched with unpleasant scents. But nevertheless this sense is not regarded in this work.

Modality

When disregarding the olfactory sense (including taste), there are three senses left: visual, auditory and haptic. For the application in ADAS it is useful to separate the haptic into tactile and kinesthetic. Visual warnings are very common. There are, for example, traffic signs that warn of curvy roads, product labels like ”smoking kills”, and warning symbols on containers with acids that inform us that the contents are ”noxious” (see Fig. 2.15). Auditory warnings are also used often. Sirens are used, for example, in industries (e.g., fire) or in war (e.g., air attack). Beeps are used on personal computers or in cars, e.g., when leaving the headlight on. The haptic (or tactile) channel has been used rarely. One can find them in aircrafts (e.g., shaking yoke) to caution against stalling or rumble strips on the street indicating the car is leaving the lane.

Intensity

Another physical attribute of a warning is its intensity. It is necessary to distinguish physical intensity and perceived intensity, respectively urgency. These two are not always in linear dependency. This dependency of physical qualities and the perceived urgency is the object of investigation of the so-called *Urgency Mapping* (see 2.2.5).

For visual warnings, the classic intensity is size, luminance, or blink frequency. Color is a special case. Color is a physical attribute, not intensity,

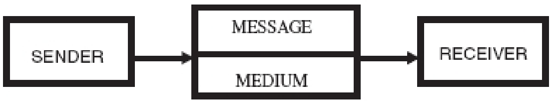


Figure 2.16: Basic communication model

but it has an effect on the perceived urgency. The intensity of auditory warnings is varied most of the time by amplitude, duration or pulse rate. In analogy to color, frequency can be named here. With haptic warnings intensity depends on the actuator used. But in general it is correct to state that force and duration are the parameters to look at.

One general request by the ISO (2005) is that the combination of physical attributes should attract the attention of the receiver without startling him.

Position/Direction

A warning has a position of its own. This is, for example, the location of the traffic sign, the loudspeaker or the haptic actuator. Some haptic solutions, such as a brake pulse in a car, do not have a position, but indicate a direction. As in the case of the example of an ADAS induced brake pulse, this would be in the direction of acceleration of the driver's body.

2.2.2 Warning Processes

Two models have been used extensively in theoretical approaches regarding warnings: communications theory and human information processing theory. The theory of communication by Shannon and Weaver (1963) is the common basis in the first approach. The pattern by Shannon and Weaver is usually simplified to a system that works with three components (see Fig. 2.16). From this perspective, communication involves a sender, a message and a receiver. Each component can provide a possible definition of a warning (T. J. Ayres et al., 1994):

- Sender: A warning is any message intended by the sender to provide information about possible negative consequences.
- Message/Channel: A warning is any message about possible negative consequences of an action (or inaction) that meets some criteria of message content and form.
- Receiver: A warning is any message interpreted by the receiver as providing information about possible negative consequences of an action (or inaction).

When working with ADAS, all perspectives (Sender, Message and Receiver) play an important role. In this analogy, the ADAS represents the Sender. Information, which is gathered by sensors and computed, results in an internal value which the system judges as harmful and then sends out a warning. The warning (Message) is sent through a certain Medium and may be perceived by the driver (Receiver). The role of the Receiver is very important. His interpretation of the Message results in action or inaction and, through that, an accident or the prevention of it. It has to be kept in mind that in the end the interpretation of the Receiver is one of the key factors. When designing an ADAS (with warnings) a lot of effort has to be spent on sensors and algorithms to precisely detect the hazard. But maybe as important is the development of a well-designed “Warning Message” to assure the fast and correct interpretation by the Receiver. If the system does not act autonomously, only the driver’s compliance closes the loop. As Meyer (2004, p. 203) says, ”Research on warnings and decision aids is research on decision making”.

There is more than one approach to describe the above mentioned warning process from the view of the Receiver. There are, for example, models by Lehto (1996), Wogalter, Conzola, and Smith-Jackson (2002), and Rogers, Lamson, and Rousseau (2000). All these models help to organize the influences concerning warnings. But these systems were created for static warnings. Warnings in a ADAS are always dynamic warnings.

Static warnings are, for example, on product warning labels or working area warning signs. The warning is always there and the receiver has to look for it actively. Good examples of static warnings are given in Figure 2.15. In contrast, dynamic warnings are “sensor-based signaling systems” (Bliss & Gilson, 1998). The warning is only sent when the system detects a hazardous state in the environment. A smoke alarm is an example of a dynamic warning. Static warnings are usually visual. Dynamic warnings can be any modality. There are several potential advantages of using dynamic warning systems (Laughery, 2006):

- ”Hazards could be warned only when they exist, reducing the problem of habituation to a permanent warning.
- The onset of a warning when the hazard is initially detected has the potential of more likely being noticed and encoded.
- Detectors can supplement people’s sensory abilities, such as the detection of carbon monoxide or radiation.”

2.2.3 Warning Process

In a review, Rogers et al. (2000) identified the influencing variables that other researchers studied in the context of visual warnings. Thereby, they

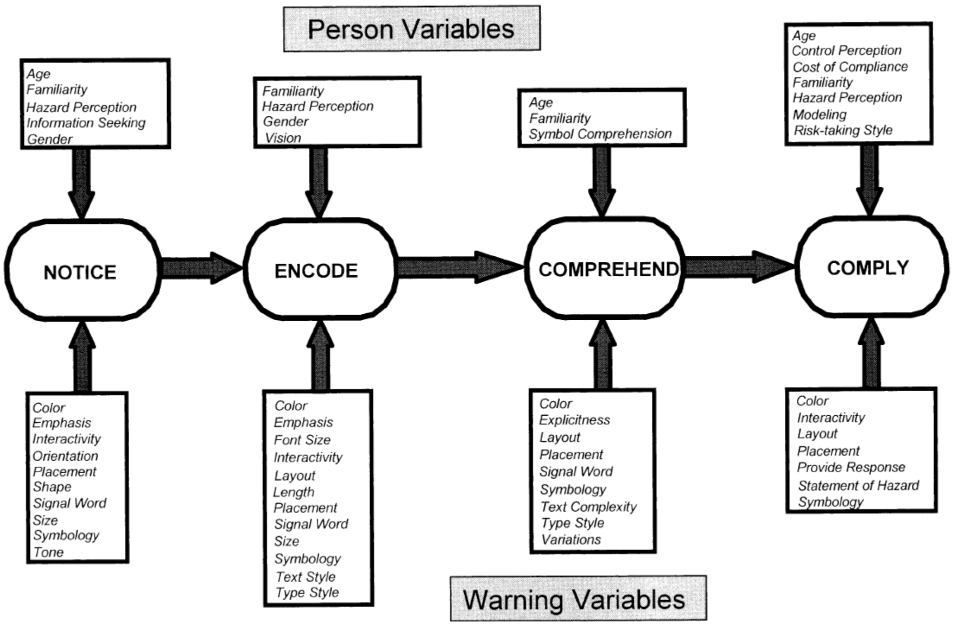


Figure 2.17: Moderating variables for static visual warnings (Rogers, 2001)

developed a list of potentially influencing variables (cf. fig. 2.17). These variables were separated into two broad categories: person variables and warning variables. As stated earlier, the influence of the modality on the receiver process will be of great interest.

Another way to organize warning literature is to separate warning factors that (1) influence noticing and encoding warnings, and (2) factors that influence compliance decisions (Laughery, 2006). Within each of these two warning objectives, influences can be organized on the basis of warning system design factors and person or situational factors.

2.2.4 Reliance and Compliance

The term *compliance* can be used to denote the response when an operator acts according to a warning signal. This means the operator follows the instruction of the warning signal. The term *reliance* refers to system state where no alarm is given and the operator does not take precautions. Reliance and compliance are the major dependent variables in warning research. These operator reactions show if the warning is effective or not. Because this part is so important for warning research it is split in three sections: Quantitative view, motivational view, and influencing factors.

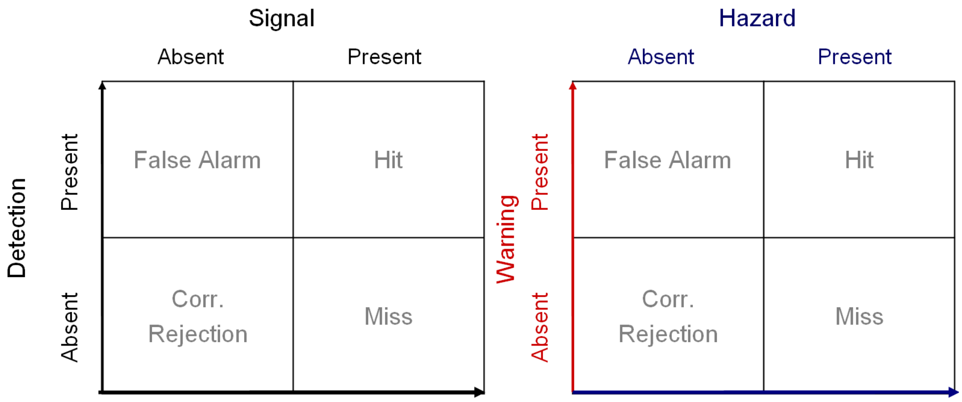


Figure 2.18: Classic Signal Detection Theory (left) and applied (right)

Quantitative View

To describe and understand the reactions of users, several theories have been employed. One of the most used theories is the classical Signal Detection Theory (SDT) (D. M. Green & Swets, 1966). This theory is a means to quantify the ability to discern between signal and noise. Detection of a signal is dependent on two factors: sensitivity (d') is the physical ability to discriminate a signal in noise. The bias (β) is the propensity of the receiver to detect the signal, due to, for example, motivation. Four possible outcomes can occur: a signal may be presented and detected (a hit), a signal may be presented but not detected (a miss), the system/receiver may respond even though no signal is present (false alarm), and the system/receiver may refrain from responding when no signal is present (correct rejection). In Fig. 2.18 the classic SDT pattern is shown on the left. On the right side this pattern is applied to detecting a hazard. To diagnose the Receiver's performance, the receiver operating characteristics (ROC) can be plotted. The ROC is a plot of the hit probability, versus the false alarms probability, for all possible values of β and a fixed value of d'. Interestingly, the SDT plays a role as well for the sensors and algorithms of the assistance system as for the human operator. The SDT is used to describe the performance of the technical sensor or the human operator.

There is a very interesting theoretical work by Sorkin and Woods (1985) about Systems with Human Monitors. They assume a two-step signal detection scheme for an, what they call, alerted-monitor system. In the first step the automated monitor has to detect the signal (e.g., hazard). That activates the alarm, which the human operator has to detect. As a response to that, the operator has to detect the hazard and react appropriately. In their theory, a prevention will be only given when both "sensors" (automated and human monitor) detect a signal. That means the operator does not detect hazardous states without being warned. As common in SDT, the automated monitor and the operator work with a sensitivity (d') and a bias (β). Sorkin and Woods (1985) show with the SDT what happens when the human operators d'_h and β_h is influenced by the β_a of the automated system. This is interesting because β_a is usually set by the engineer in contrast to the sensitivity which is a hardware problem. In a two-stage model the dependencies from one system has great impact on the other. It could be that β_h is some function of β_a. This means that, as the number of false alarms of the automated monitor increases (the bias is high), the human operator requires more evidence to confirm the warning (the bias is low). In a system with a human acting like this, it is impossible to achieve either high hit rates or high false alarm rates (see Sorkin & Woods, 1985, p.61, for details). Another possible dependency could be that d'_h is a function of β_a. An example would be that high automated warning rates lead to situations where the operator either ignores some alerting signals or makes observations with a reduced detectability. The phenomenon that people tend to ignore alarms when they experience many false alarms is a known problem in research and called the "cry wolf phenomenon" (Breznitz, 1984). On the other hand, if alarms occur infrequently, the operator will observe the environment on every occurrence of a warning. It is essential to keep in mind that these dependencies can be investigated on a mathematical level with the help of the SDT. And the work of Sorkin and Woods (1985) proved "(...)the optimal criterion placement for one stage of a two-stage detection system may not be identical to optimal placement in the single-stage case" (p.70).

Motivational View

One approach to understanding the decision of the human operator to comply or not is the Subjective Expected Utility (SEU) model by Edwards (1954). The model assumes that the decision process follows a relatively simple mathematical model. The subjective expected utility of an action is the sum of the perceived probability of each outcome, multiplied by the desirability value of that outcome.

$$U_{comp} = P_{ncomp} \times V_{risk} - P_{comp} \times V_{risk} - C \qquad (2.5)$$

Equation 2.5 represents the SEU model, where P is the probability of the outcome, which in this case is risk of, for example, an accident; P_{comp} is the risk of injury if the warning is complied with; P_{ncomp} is the risk if the warning is not complied with; V_{risk} is a value corresponding to the risk inherent in the task and C is the cost. Factors included in the costs could, for example, be or include time to comply and wearing uncomfortable protection.

Another theory of the same tenor is the expected value analysis (e.g. Edworthy, 2001; Meyer, 2004). This theory is based on a straightforward mathematical formula. Whether or not a person complies to a warning depends on the expected value (EV) of the outcomes. A rational risk neutral decision is one that maximizes the expected value (EV) of the outcomes. The EV for an action is the sum of the products of the probabilities of the possible outcomes following this action and the values of these outcomes.

$$EV = \sum_{i=1}^{n} p_i V_i \tag{2.6}$$

It is assumed that there are two system states: Normal and Failure with the probabilities p_N and p_F. In the example of the smoke alarm, Normal means there is no fire, failure means there is a fire. The person can act at any time as if the system state is Normal n(e.g., stay in the house) or Failure f(e.g., leave the building). As in the SDT there are four values of outcome: 1) $V_{n,N}$ correctly staying in the house, 2) $V_{f,N}$ acting as if there is a failure, e.g., leaving the building without a fire, 3) $V_{n,F}$ staying in the building although there is a fire and 4) $V_{f,F}$ correctly leaving the building when there is a fire. The person should always respond (e.g., leave the building) when the EV for f is higher than for n.

$$EV_f > EV_n \tag{2.7}$$

The formula for EV_n is

$$EV_n = p_F V_{n,F} + (1 - p_F) V_{n,N} \tag{2.8}$$

and for EV_f is

$$EV_f = p_F V_{f,F} + (1 - p_F) V_{f,N} \tag{2.9}$$

This approach seems to be very clear. But one drawback, for example, is that the compliance rate should not change over time. Unless, for example, one assumes that the perceived probabilities change due to familiarity.

Influencing Factors

Dingus, Hathaway, and Hunn (1994) showed in two field tests how costs affect compliance. In the first study 920 racquetball players were unobtrusively observed. In order for players to be considered compliant in the test domain, they were required to wear eye protection. The experimenters varied the location of warning signs, the warning information content, and the cost of compliance. The realization of cost variation was achieved by 1. eye wear provided just outside the court (low cost), 2. walk 18m to a checkout booth to check out eye wear (medium cost), and 3. leave the building to obtain eye wear (high cost). Only players who didn't bring their own eye protection were included in the analysis. In the low cost condition, 60% of the players used eye wear. For the middle and high level of cost, compliance rates were 0%. The other independent variables did not influence behavior significantly.

From this and other experiments, there is evidence for the assumption of the SEU model, that warning effectiveness decreases as the costs of compliance increase (DeJoy, 1994; Dingus et al., 1994; Rogers et al., 2000).
In literature overviews concerning visual warnings only, Laughery and Brelsford (1994) as well as Rogers et al. (2000) list factors that have been demonstrated to influence compliance. Rogers distinguishes person variables and warning variables. There is evidence that *familiarity* with a product usually leads to less compliance with the warning instructions (see also DeJoy, 1994; Laughery & Brelsford, 1994). When concerning static warnings, people who are familiar with a product are less likely to look for, notice and read warnings. For many products, dangers are seldom events and thus users do not experience mishaps. Laughery and Brelsford (1994) proposes that the more a person uses a product without experiencing a safety problem, the less hazardous they perceive the product to be. This also influences *control perception*, which manipulates compliance in the same way as familiarity does. Regarding static on product warning labels, gender and age play a minor role. But female receivers comply more often to warnings than men do (Laughery & Brelsford, 1994). The results concerning age have not been completely consistent. Thus, there is no general statement to the coherence of age and compliance (Laughery & Brelsford, 1994; Rogers et al., 2000). Another finding is that *hazard perception* determines warning effectiveness (Laughery & Brelsford, 1994). This finding is often referred to in contrast to probability. People comply when they expect the outcome to be dramatic. They will not comply just because a negative outcome is likely. But this connection is not always that straightforward. Another person variable is *risk taking style*. Risk taking style is associated with control perception and high values for risk taking leads to less compliance with warnings. The coherence of operator compliance and hit to false alarm ratio was the focus of an experiment done by Getty, Swets, Pickett, and Gonthier (1995). The downside of the study is the small number of participants (n=4). These participants had to fulfill a continuous tracking task. When there was a visual alarm on the same screen as the tracking task they had to respond to it by halting the tracking task and pressing a special button. Getty et al. (1995) varied what they call the positive predictive value (PPV) of the warning. The PPV is calculated by occurrences of states of the signal detection theory scheme (see Fig.2.18). The PPV is defined as $n_{hit}/(n_{hit}+n_{FA})$, the proportion of positive responses that truly indicate a dangerous condition[2]. The PPV was set variously at 0.25, 0.39, 0.50, 0.61, and 0.75. The participants could earn extra money both for good performance on the tracking task and for rapid response to true alarms. The participants could not double check the correctness of the alarm before reacting but were informed after each response. Letting go of the tracking task under optimal tracking conditions enhanced performance

[2]In Signal Detection Theory the PPV would be the sensitivity d' of the system.

of the automated continuation of this task during their alarm deletion. The analysis focused on the time between the alarm and the response to it. The subjects responded slowly to low PPVs and quickly to high PPVs to maximize the net gain from the benefits and penalties imposed. This means people's compliance decreases when the false alarm rate increases. Getty et al. (1995, p.31) state, "that the PPV is usually low because the prior probability of a dangerous condition is characteristically very low. (...) System designers typically wish to minimize the probability of missing a dangerous condition and hence permit a decision threshold that is lenient enough (a false positive proportion that is high enough) to further decrease the PPV."
A simulator study conducted by Bliss and Acton (2003) investigated how collision alarm reliability affects driving. 70 participants drove along a highway route in a stationary simulator. A collision avoidance warning system was implemented in the simulator. The warning system indicated fast approaching cars from the rear, left rear or right rear. If the alarm was true, drivers were told to swerve to avoid being struck from behind by the approaching car. The alarm reliability was manipulated among three groups: 50%, 75%, or 100% true alarms, the rest were false alarms. The alarm stimulus, audible for 4s, consisted of regular 1000 Hz sine wave pulses at approximately 90dB(A). Every participant attended in two consecutive experiments, which lasted 20 min each. In experiment one, the warnings sounded from the center console, in experiment two the warning was spatially aligned. This means the warning came from left rear, rear, or right rear depending on the threat's location. Both experiments reveal similar results. The higher the alarm reliability, the higher the frequency of reactions. Also the appropriateness of driving responses (e.g., swerving in the right direction) rose with alarm reliability, but the difference was not significant. Surprisingly, the 50% group had fewer collisions than the 100% group. The authors explain that effect so that the members of the 50% group checked the rear mirror more deliberately, than the 100% group. Additionally, they state, "... some members of the 75% and 100% groups seemed to fall into a comfortable routine of swerving slightly of making a *token*[3] reaction." (Bliss & Acton, 2003, p. 507).
In a fixed-base simulator, Abe and Richardson (2004) conducted an experiment to investigate driver trust in a Forward Collision Warning (FCW) System. The experimental tasks were car following and collision avoidance on a single-carriageway urban road. The subjects drove at 72 km/h following a lead car with a 2s headway. The lead car decelerated unpredictably with 0.9g. The experiment consisted of two sessions. In the first session, the driving task was completed without a FCW and the second session with a FCW. The FCW used an auditory buzzer alarm. The FCW operated with three different timings: early, middle and late. After each deceleration event in the alarm session the drivers had to rate their trust in the warning sys-

[3] A pro forma movement

tem on a 10-point scale. Objective measures like brake reaction time and accelerator release time were also recorded. The results show that alarm timing has an influence on the driver's trust in the system. Namely that the late warning leads to worse trust ratings than the other timings. Abe and Richardson (2004) concluded that drivers already reacted to the thread in the late warning condition when the warning sounds. Trust ratings in this paper increase as the time gap between alarm onset and brake application increases. Abe and Richardson (2004) explanation for this result is that the earlier the alarm, the more time the driver has before needing to brake and therefore the trust is greater. Another explanation could be that the participants experienced two kinds of system failures in these situations. As they braked earlier than the late warnings, first they experienced a "Missing " and then an FA, because they were already braking.
In a follow-up study, Abe and Richardson (2006) use the same simulator setup. This time there are just two alarm timing conditions (early and late), but three different speeds (48.3, 96.5 and 112.6 km/h) and two time headways (1.7 and 2.2s). The subject's tasks are the same. They were confronted with all 12 experimental conditions. Again the first session was accomplished without alarms and the second with alarms. The results again show less trust in systems with a late warning. Interestingly, this is true especially for the long headway condition. This may support the idea of a double failure. The subjects "saw it coming" a long time before the alarm went off. Driving speed does not have a significant impact on trust or driver performance.
The two studies in this paragraph analyze subjective assessments of trust in the system, but disregard potential "annoyance" of the warning. Unfortunately, annoyance of a warning rises the more sensitive a system is set, because it leads to more unnecessary alerts.

Wickens and Dixon (2005) undertook a meta-analysis regarding the benefits and costs of imperfect automation. They only included experiments which studied *diagnostic aiding*. This generic type of automation is filtering or focusing attention on information deemed to be of interest and forming inferences of the state of the world by integrating information. It does not recommend or select a special course of action or even implements it. They wanted to find out if there is a value of reliability of automation, below which automation becomes useless or is worse than human action alone. The included studies all had a concurrent main task and a secondary monitory task. The secondary task was assisted by the automation. 22 studies were evaluated by comparing baseline performances (without automation) with the performance of different reliability conditions in the studies. For the meta-analysis, the baseline performance was set to 0. When the authors of the primary literature found a significant difference between the baseline and automated condition, Wickens and Dixon (2005) assigned better performances than baseline a +1, worse a –1. If there was no significant difference, they assigned the result a zero. They calculated a regression analysis for the secondary task performance and revealed a crossover point (from cost to benefit) at a reliability value of r=0.70. That means when the reliability of the automation was less than 70% the performance in this task was worse than without the automation. Interestingly, there was almost no impact of automation reliability on the primary task. When Wickens and Dixon (2005) took a look at the workload of the participants resulting from the main task, they examined that it had an impact on reliance on the automation. The higher the workload, the higher the dependence on the automation. Wickens and Xu (2002) alluded to the same topic by finding out that people tend to follow the advice of a faulty automated system more when they are in a dual task, rather than in a single task. The overall result of Wickens and Dixon's meta-analysis is quite similar to what Lee and See (2004) state in their literature review: "(...)some evidence suggests that below a certain level of reliability, trust declines quite rapidly. The absolute level of this drop off seems to be highly system and context dependent, with estimates ranging from 90% and 70% to 60%" [p. 72]. But what is said about context dependency by Lee and See (2004) is correct for the meta-analysis result, too. 70% is not a set value. It differs from task to task. One drawback of the meta-analysis is that system reliability was not differentiated by false alarms and misses. As suggested by the literature so far, the impact of these two diverse system failures on the human operator is quite different.

There is a focus on this difference in a study by Dixon, Wickens, and McCarley (2007). They investigated the independence of compliance and reliance. To gain insights into this topic they manipulated automation in their experiment so that it was False Alarm prone or Miss prone. Participants performed a compensatory tracking task with a joystick and a cognitively demanding system monitoring task. Some participants performed the monitoring task unaided and others performed the task with an automated diagnostic system that was FA prone, miss prone or 100% reliable. In the monitoring task, the participants had to respond to a system failure with a press of a button. In the beginning, the subjects were told how reliable their automation for the tracking task was. The results revealed that subjects fulfilled the tracking task worse in the FA condition than in the 100% condition. This data was only collected before a system failure occurred. Therefore, the authors assume that the poor performance is affected by a higher workload demand caused by a loss of reliance in the automation. The system failure detection was worse in the FA group than in the miss condition. There was no difference between the miss group and the baseline, but the FA group performed worse than the baseline. The misses did not effect the compliance as opposed to the FA, which did degrade operator compliance. Thus, this study provides evidence that reliance and compliance are independent as implied by the model by Meyer (2004). Dixon et al. (2007) summarize that the FA prone condition was more harmful to overall performance than the miss condition. FA prone automation influenced both compliance and reliance negatively, whereas the miss condition reduced reliance only. Thus, the FA hurt the automation task more than the misses, and the FA hurt the tracking task at least as badly as the misses did. "Thus it is clear that FA-prone automation affects total performance by degrading reliance (affecting prealert concurrent task performance), by timesharing disruption (affecting postalert concurrent task performance), and by reduced compliance (affecting alerting task performance), whereas miss-prone automation degrades only the first of these (reliance) (...)"(Dixon et al., 2007, p. 571).

It could be shown that compliance and reliance are indeed two separate responses (e.g. Meyer, 2001). In this study a signal detection task supported by a binary warning had to be accomplished. When operators gained experience, reliance decreased, whereas compliance didn't change over time. Additionally, the validity of the warning system influenced compliance more than reliance.

So far, most of the theoretical approaches as well as the experiments showed negative influences on operators' trust and performance due to FA and misses. There is an interesting conclusion in a literature review by Wickens and Xu (2002), who state that operators may be more "forgiving" (and hence more likely to retain reliance) on automation if the source of the failure is external to the automation itself, rather than failures of the automation (e.g., software bugs). Still, literature so far evinces that especially false alarm prone systems raise a problem with user compliance. Regarding Collision Avoidance Warnings, one topic is of major importance: the a priori possibility or base rate of potential collision scenarios. Parasuraman, Hancock, and Olofinboba (1997) calculate with the estimated base rate of 173 crashes for every million lead vehicle stops, or a p of 0.000173 for freeway driving. A base rate with a probability like this has a powerful influence on the true alarm rate. How strict should the decision threshold respectively β be? Should the system tuning be as close to $\beta = 1$ as possible? Parasuraman et al. (1997) say "no". The rationale for this answer is that with a system like that, a driver would experience the first warning just before the crash. Hence the driver may not understand the warning or react fast enough. Farber and Paley (1993) speculated that an ideal detection algorithm might be one that gives an alarm in collision-possible conditions, even though the driver would probably avoid a crash. Although technically a false alarm, this type of information might be construed as an aid in allowing improved response to an alarm in a collision likely situation. Thus all false alarms need not necessarily be harmful. This assumption was proven by Lees and Lee (2007). In their experiment, the participant experienced FA and unnecessary alarms. The unnecessary alarms are defined as alarms in situations similar to the real threat but not judged as critical by the driver. The study revealed that FAs diminished trust and compliance, whereas the context associated with unnecessary alarms fostered trust and compliance during subsequent events. Therefore, these results support an extension of the possible outcomes of the signal detection theory. The results can be interpreted as such that an additional dimension in Fig. 2.18 (see page 37) could be needed. This would have to reflect the operator's understanding of the situation.

2.2.5 Urgency Mapping

In the context of aviation, an awareness of maladjusted alarms arose in the early 1980s. Examples of the problem are alarms were too loud, too numerous, in- distinguishable from one another, not standardized and not mapped systematically to the situations that they indicated (E. Hellier & Edworthy, 1999). On the side of the operators (in this case pilots) that lead to misunderstanding the warnings, there were long learning phases for the systems, and hence dangerous situations. To solve this problem, Patterson (1982, cited in Edworthy, 1994) recommended that non-verbal auditory warnings should be constructed with different levels of urgency. A prerequisite for this is that a user gets the impression of a certain level of urgency when he perceives a warning. Urgency Mapping calls this "perceived urgency". The goal of Urgency Mapping (UM) is to match the urgency of the indicated situation and the perceived urgency conveyed by the warning (Edworthy, 1994). "UM (...) should thus allow warnings to be mapped meaningfully to the situations that they indicated and facilitate an appropriate operator response (...)" (E. Hellier & Edworthy, 1999, p. 168). UM was originally introduced for non-verbal auditory warnings (Edworthy, 1994). Hence the corpus of research addresses acoustic signals and the examples given will be limited to this modality. In the meantime, UM is also applied for visual warnings (e.g. Braun & Shaver, 2001). UM does not develop a particular warning with a number of versions to communicate e.g., low, medium, and high urgency for a dynamic progress (E. Hellier & Edworthy, 1999). To attain the goal of UM it is necessary to quantify the relationship between changes in the objective parameters of the warning (e.g., amplitude of a sound) and changes in the subjective perception of urgency. To do that, UM avails itself of psychophysical techniques – first and foremost Stevens Power Law (Stevens, 1957). The relationship between the changes in objective and subjective parameters is described by Stevens Power Law with the following equation

$S = kO^m.$

Here, S is the value of the subjective parameter, O is the objective parameter, and k and m are the intercept and slope of the line of best fit. The line is the function of subjective (x-axis) and objective (y-axis) parameters in a logarithmic coordinate system. For the purpose of UM, Stevens Power Law was adapted in a way so that S is the perceived urgency and O is the value of warning parameter (e.g. amplitude of sound) (E. J. Hellier, Edworthy, & Dennis, 1993). The usual procedure is to conduct laboratory experiments to identify how specific parameters of a sound affect the change of perceived urgency. To do that, one parameter of a sound (e.g., amplitude, pitch, or duration) is picked. This parameter is the only thing that is changed in the experiment. The subject has to listen to the sound and than rate the perceived urgency. Several scaling procedures are possibly applied (e.g., free modulus magnitude estimation or paired comparison). In 2.4, ex-

Table 2.4: Power function exponents and relationship between warning parameters and urgency (Hellier & Edworthy, 1999)

Warning parameter	Exponent	Increment to double urgency
Pitch	0.38	× 6.0
Speed	1.35	× 1.6
Repetition	0.5	× 4.0
Inharmonicity	0.12	× 307.0

amples of results for sound parameters are given. In this comparison, Speed is the most effective parameter with m = 1.35. Speed is the period of silence between two sound-pulses. If this pause from a certain warning is shortened by 1.6 times, the perceived urgency is doubled. The most ineffective parameter is inharmonicity with m = 0.12. Interestingly, when combining two parameters/dimensions of a warning, the perception of urgency works additive (E. Hellier & Edworthy, 1999). With the knowledge of the experiments done, sounds can be created which communicate a certain level of urgency. The next step is to rate the urgency of the dangerous situation and then implement a warning that matches it. Usually, a number of warnings matching the number of danger situations is picked. Warnings and situations are ranked and then matched to do the UM.
The insights about the connection of acoustical changes and perceived urgency are stable for unknown sounds. But if sounds are familiar or similar to a familiar sound, the UM effects are inferior (Guillaume, Pellieux, Chastres, & Drake, 2003).

In recent research another factor becomes more and more relevant: annoyance. Marshall, Lee, and Austria (2007) examined several acoustic parameters with psychophysical techniques regarding perceived urgency as well as perceived annoyance. The goal was to identify parameters which have great impact (large m) on urgency, but a small impact (small m) on annoyance. The rationale behind that is to find a parameter to modify the urgency of the warning without creating an annoyance to the driver. Very promising was the parameter pulse duration: Longer pulse duration lead to more urgent (m = 0.80) and more annoying (m = 0.28) warnings. But because of the smaller m in annoyance, a change in pulse duration evokes a greater change in perceived urgency than annoyance.

2.3 User Interfaces for Driver Assistance Systems

Driver Assistance Systems can be classified in longitudinal and lateral systems. The group of longitudinal systems includes, for example, Adaptive Cruise Control (ACC), ACC with Stop & Go extension, Intelligent Speed Adaption, Following Distance Indication, and Forward Collision Warning (FCW). Lateral systems are, for example, Blind Spot Detection and Lane Departure Warning. All of these systems have been realized and are on the market already. This thesis focuses on Forward Collision Warning systems, which is part of the group of Collision Warning Systems (CWS). The main purpose of CWS systems is to prevent hazardous situations by warning the driver. The driver's reactions in relation to the hazard should be quickened or refined. In addition, the warning may serve to educate the driver by providing feedback concerning desirable practices or unsafe acts (Lerner, Kotwal, Lyons, & Gerdner-Bonneau, 1996).

To provide fundamental knowledge, the essential functionality of a FCW is explained here in a few words. A FCW basically consists of a sensor, a computing unit, and an actuator to issue the warning (e.g., a loudspeaker). The sensor (e.g., radar, lidar or camera) detects the distance to an object in the direction of motion. In the computing unit this information is fused with data about the own velocity and, out of this, relative velocities are computed. By means of these parameters a decision value is calculated. When this value exceeds a certain threshold, a warning is issued. The process described is similar to the process of a human. With the information of the ego movement and the position and dynamics of the external objects, the system calculates a future state. This is comparable to what Endsley (1995) calls "Projection of Future Status" in her situation awareness model. If this state has been predefined in the system as being critical, a warning is issued. This is comparable to the behavior of a passenger, who shouts "Watch out!" when he anticipates a dangerous situation.

The general effectiveness of CWS on driving behavior in critical situations has been shown in several studies (e.g. Campbell, Richard, Brown, & McCallum, 2007; Kiefer et al., 1999). In a direct comparison of young and old drivers, Kramer, Cassavaugh, Horrey, Becic, and Mayhugh (2007) found out that both age groups profit by the same degree of a CWS. A study by Ben-Yaacov, Maltz, and Shinar (2002) supports the idea that a CWS, namely a tailgating advisory, can alter the driver's following behavior. Färber and Maurer (2005) report about a study with an automatic braking system. The participants' emotions after the system intervention ranged from curious to frightened to panic. The conclusion by the authors is to incorporate the human operator or driver in the development from the beginning on. Without regarding the human operator, the authors advise against the development of ADAS, especially Collision Avoidance/Mitigation systems.

Device	Glance duration (s)	Number of glances	Total glance time (s)
Turn on 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

Table 2.5: Visual glance times and number of glances for a variety of tasks (ISO, 2005)

To summarize this small introduction to CWS, one can put to record that CWS are able to support the driver and enhance traffic safety. But this is only true if the system behavior – particularly HMI – is designed to match the needs of the driver.

2.3.1 Warning Modalities

This section focuses on the advantages, disadvantages, and the particularities of the different modalities on the driver. Special focus is put on the concrete implementations in CWS and studies concerned with human factors.

To distinguish situations, one can differentiate coupled and uncoupled pairs of cars. A coupled pair of vehicles refers to a situation where a change in speed of the lead vehicle is mimicked by the driver of the following vehicle. Vehicles are not coupled when following distances are initially sufficiently great that speed variations of the lead vehicle are not perceived to be of immediate consequence to the driver of a following vehicle (ISO, 2005).

Visual Warnings

The design guidelines provided by Campbell et al. (2007, p. 4-2) state "Use visual warnings to provide continuously available information in situations where it is not critical that the visual warning will be relied upon to capture the driver's attention." This sentence tells a lot about the particularities of visual warnings. And although the sentence is trivial, it is an important one for the design of a collision warning system: A visual warning demands visual attention.

To get an impression of glance duration times for typical tasks in a car table 2.5 gives an overview. In a car, most visual displays are located in the instrument panel (behind the steering wheel). There, the displays

Type	Visual Warning
Collision Warning	Color: red Position: main glance direction Luminance: high luminance Interval: intermittent at short interval is recommended
Preliminary collision warning	Color: yellow or amber Luminance: luminous enough in daylight, not glaring in the night Interval: continuous or intermittent at long interval

Table 2.6: Warning characteristics for visual FCW (ISO 15623:2002(E))

are close to the line of sight and can be noticed with peripheral vision while looking forward onto the street. Disadvantages of the position are that the instrument panel can be obscured by the steering wheel and when a display in the instrument panel is focused, peripheral vision of the traffic environment simultaneously is hardly possible. A problem is the shifting time to focus on the near instrument panel and refocus on the street again. Infotainment systems are often located in the center console. To focus on a display in the center console, eye and head movement is necessary. Therefore, reaction times to displays in the center console are longer than in the instrument panel (ISO, 2005).

ISO Standards The ISO standard 11428 (ISO, 1996) defines general requirements, design and testing for visual danger signals. Visual danger signs shall be "clearly seen under all possible lighting conditions, clearly discriminated from general lighting and other visual signals, and allocated a specific meaning within the signal reception area"(ISO, 1996, p.2). If the light is flashing, the ISO recommends a flash frequency between 2Hz and 3Hz with equal on- and off-intervals. The warning display should be located ± 15 from the line-of-sight in the vertical as well as the horizontal field of vision. A visual warning signal should be yellow or yellow-orange. A visual emergency signal should be red. If two or more signal lights are used in one device, the red signal should always be positioned above the yellow one.

The ISO standard 15623:2002(E) (ISO, 2002) defines performance requirements for automotive FCW systems. Here a minimum number of warning stages of two is specified: a preliminary collision warning and a collision warning. The warning characteristics are listed in Tab. 2.6. To accomplish best visibility of the warning head-up displays, other virtual image displays, and displays mounted near or on the top of the instrument panel should be used(ISO, 2005).

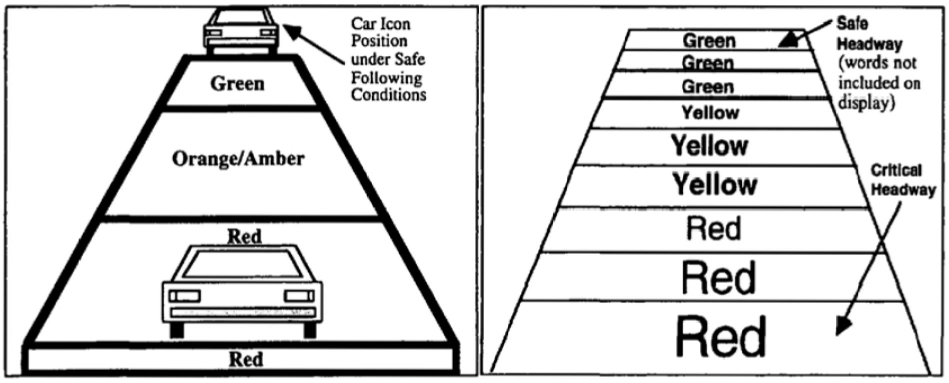


Figure 2.19: Car icon (left) and Bars display (right) used by Dingus et al. (1997)

CWS applications Different displays have been tested for CWS. This section summarizes what has been done. In three similar on-road studies, Dingus et al. (1997) examined different visual displays and one auditory signal for use in a CWS. Experiment 1 concentrated on designing a collision warning display that could be understood by the naive user and testing its effects on driver performance. 108 participants took part in that experiment. All completed a baseline drive, and then subjects were assigned to only one of three display conditions. The two experimental displays are shown in Fig. 2.19. As the distance between the participant's vehicle and the lead vehicle became shorter, new bars were displayed one below another, increasing in number and changing from green to orange/amber and then to red. The green zone corresponded to a headway of 1.6s or greater. The orange/amber zone indicated a headway between 1.1 and 1.6s, whereas the red zone indicated 0.9 to 1.1s. By the end of the red zone, all of the bars were illuminated. At any distance below 0.9s, the red bars flashed on and off at a rate of 4 Hz. The third display consisted of two squares abreast. The left one was orange/amber and flashed at 4 Hz continuously when the target was acquired and the right one was red and flashed with the same frequency when headway was below 0.9s. The participants drove about 80 km/h on a highway. They followed a confederate car, but thought the driver was another participant. The confederate car performed some light and medium braking maneuvers. The participants were distracted by secondary tasks. During the coupled headway events, the car icon display induced significantly longer headways ($p < .05$) than the bars display or the square display. And it was the only display to induce longer headways than the according baseline drive ($p < .05$). The second experiment focused on the modality to present a CA warning. The experimenters compared visual, auditory, visual plus auditory, and a digital number display, which indicated the headway in feet. The bars display worked as in experiment 1. In the auditory condition, a recorded voice said "Look ahead", when the headway fell below 1.1s . When the participant

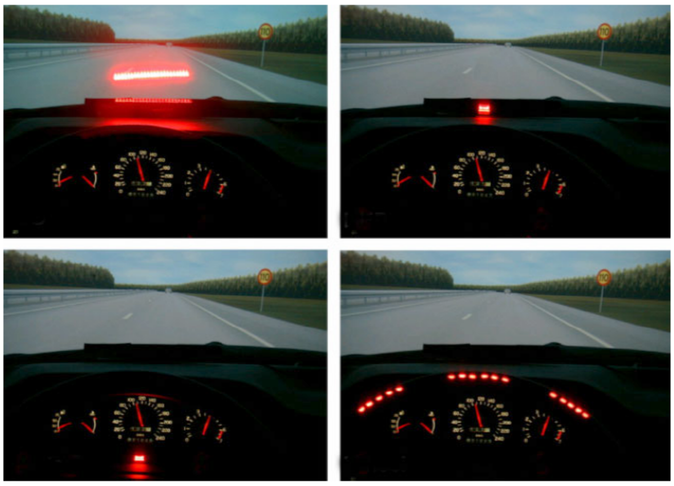


Figure 2.20: Displays investigated by Lind (2007)

closed to within less than 0.9s of headway, the verbal message changed to "Brake!". If the headway was maintained in the 1.1 to 0.9s zone, the warning "Look ahead" was repeated every 7 seconds. The combination of visual and auditory implemented both functionalities without any modification. There was no significant difference in headway between any of the conditions.
Lind (2007) conducted a simulator study in which he compared four kinds of display for a FCW. The four layouts are shown in Fig. 2.20. Each display is red and flashes with 4Hz and for a 1.2s duration. Lind calls the displays Collision Warning Head Up Display (CWHUD, top-left), High Head Down Display (HHDD, top-right), Cluster Display (bottom-left), and Steering Wheel Display (bottom-right). All of the 16 participants experienced each display. The subjects' driving task was to keep to 110 km/h. A forward vehicle drove at a fixed distance of 1.5s headway. The participants were warned on an average every 30s. The warning appeared without any threat. The main task was to react to a warning by stepping on the brake pedal. The subjects had to perform a secondary task, which was a visual search task. The data analysis (ANOVA for repeated measures) revealed significantly faster brake reaction times for the CWHUD than for any other display ($p<.05$). With the CWHUD the least amount of misses were produced (Wilcoxon paired comparison, $a=.05$). Unfortunately, intensity is not reported to be controlled in the experiment. As discussed in Section 2.1.6, reaction time decreases with higher intensity and might have contributed largely to the effect. The CWHUD solution has been in production at Volvo since 2007.

Text message and Icons From 50 candidates the CAMP FCW icon (see Fig. 2.21) was found to be the one with best comprehensibility (Kiefer et

Figure 2.21: CAMP one-stage FCW symbol (Kiefer et al., 1999)

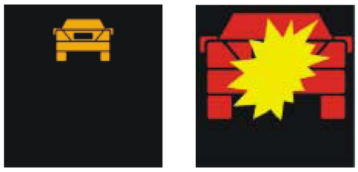


Figure 2.22: GM two-stage FCW symbol (Campbell et al., 2007)

al., 1999). It is recommended for the use in a one stage warning system. When using a two stage warning system, the design guidelines by Campbell et al. (2007) recommend the GM warning symbols (see Fig. 2.22 (NHTSA, 2002)).

Intensity Intensity in visual displays can be changed physically via size, flashing rate, and luminance (see also (ISO, 1996)). The most common way to design intensity levels for warnings is color. Numerous studies have reported a consistent relationship between color and perceived hazard (e.g., Braun & Shaver, 2001; Rogers et al., 2000). The ascending order white, green, blue, yellow, orange and red results in increased perceived intensity. In text warnings the ascending order is *warning*, *caution*, *danger*, although the distinction of *warning* and *caution* is not safeguarded (Braun & Shaver, 2001; Wogalter et al., 2002).

Acoustic Warnings

One of the major advantages of acoustic signals is that the recognition is independent of head position and directed attention. In addition, they are comprehensible to users who do not read and are very good at attracting attention. According to the multiple resource model, the interference by an acoustic signal with the visual main task (driving a car) is smaller than with a visual signal (Wickens & Hollands, 1999, chapter 11).

As with every warning, the acoustic signal shall convey the type of threat, threat level, location of threat and behavior guidelines. The conveyed urgency can be manipulated amongst other things by loudness, frequency spectrum, harmonicity, rhythm, and length (e.g., Catchpole, McKeown, & Withington, 2004; E. Hellier & Edworthy, 1999). One problem with auditory signals is that partially or completely deaf people retain their driving license in most countries. Therefore signals denoting a safety critical state have to be presented in another modality, too (ISO, 2004, Req. 7.1).

A. Tan and Lerner (1995) defined and weighted the key attributes of the auditory warnings in vehicles by expert judgments. The highest weighted attributes are listed in Table 2.7.

Attribute	Definition	Ranking
Conspicuousness	The auditory warning is noticeable within other noises and sounds in the vehicle	9.4
Discriminability	The auditory warning is uniquely identifiable and distinct from other sounds in the driving environment	9.2
Meaning	The auditory warning unambiguously conveys or suggests the meaning of, e.g. imminent crash	9.0
Urgency	The auditory warning conveys the proper sense of importance motivating an immediate response	8.8
Response compatibility	The auditory warning causes the driver to anticipate and prepare for an emergency response	8.6
Experience compatibility	The auditory warning follows natural and learned relationships of users such as sirens associated with emergency	7.6
Startle effect	The auditory warning does not startle or surprise the driver causing a delayed reaction	7.6
Orienting response	The auditory warning can be easily localized in 3D sound space, and causes the driver to look in the direction of the hazard	6.8
Appropriateness	The auditory warning is compatible with the vehicle environment	5.7
Annoyance	The auditory warning is not annoying or irritating to the driver (assuming minimal false alarm rates)	4.4
Musicality	The auditory warning is melodious	2.3
Naturalness	The auditory warning does not appear artificial or computer generated	2.2
Loudness	The sound has high volume and intensity	–

Table 2.7: Key attributes of the auditory warnings in vehicles (Tan & Lerner, 1995)

One of the often cited advantages of acoustic warnings is that they are localizable. Thus an acoustic warning facilitates a visual target search. Laboratory research has shown that auditory spatial cues significantly reduce time to locate and identify a visual target (e.g., Rudmann & Strybel, 1999; Ho & Spence, 2005). The location of the threat should be indicated by the localization of the warning signal. Several localization studies showed that in a left/right discrimination task there are distinct advantages afforded to the listener by a broad band noise, and that severe band-stop filtering noise can significantly reduce localization acuity (e.g., Catchpole et al., 2004). The addition of noise to a tone enhances the precision of localization and therefore should be used.
A. Tan and Lerner (1996) conducted an experiment to investigate the ability to localize warning sounds in a car. They tested 6 warning sounds (3 tonal

and 3 speech output) played on specific loudspeaker combinations of a total of 12 speakers installed in the test car. By the combination of speakers, 16 different directions could be simulated. The warning sounds included a low-fuel warning from an aircraft flight deck (obtrusive siren), an "off-the-shelf" warning buzzer (Hi-Low tone sequence), and a repeating pattern warning incorporating several recommended warning characteristics from the literature. The speech output warnings repeated the word "Danger" by a recorded female voice, a recorded male voice, or by a synthesized male voice. A background noise recording of the interior of a vehicle while the vehicle was driving on a highway at 88.5 km/h (55 mph) was continuously present. The subjects (n=24) were seated in the driver's seat of a stationary car and had to indicate the direction of the played warning with a joystick mounted in the middle console and then press a joystick button. They were asked to be as fast and as precise as possible. As a secondary task, they watched a video of a vehicle driving on a highway on a TV screen and had to announce every time the car in the movie crossed a bridge. The dependent variables were reaction time (initial joystick movement), decision time (joystick button press), accuracy (degree from correct localization), and azimuth direction of response. On average, the mean RT for younger subjects was 0.95s and the older drivers were approximately half a second slower. There was no overall sound effect. The low fuel sound produced faster responses in the younger population. The other non-speech alerts resulted in slower response times in the older subjects. Since some conditions produced very poor performance, the overall mean error was just over 30°. Some errors exceeded 90°, which indicates a perceptual reversal and could lead the driver's attention away from the hazard. Here are some examples: The highest precision resulted from the combination of right A- and C-pillar (4.4 mean error), and right C-pillar (7.8) and left C-pillar (10.1). For the front center (both A-pillars) a mean error of 27 effected.

Auditory signals can be distinguished by the categories: Acoustic signals and speech output. The acoustic signals can be further distinguished in tonal signals and auditory icons.

Tonal Signal For clarification of wording: Usually a warning sound consists of several properties. A pulse is a sound contained within one amplitude envelope, which has an onset, an offset, and a specific duration. A pulse can be repeated several times with intervals of silence between each pulse. The resultant unit is referred to as a burst of sound. The burst forms the basis of a complete warning sound.

Wiese and Lee (2004) investigated auditory alerts for in-vehicle information systems in a fixed-base simulator. In two studies. conventional tonal signals were used as FCW. The warning was taken from the CAMP studies

(Kiefer et al., 1999). They manipulated the sound to implement a high and a low urgency warning. The parameters chosen to differentiate the urgency levels were loudness and density. The loudness of the low urgency sound was at 61dB(A), the high urgency sound was at 78dB(A). There were 20 consecutive bursts in each sound. The low-urgency collision warning was composed of three pulses of sound of 0.107s duration, interspersed with 0.007s of silence. At the end of the third pulse, there was a 0.113s period of silence before the next burst began. The burst density for the low-urgency collision avoidance warning was 0.76. The density for the high-urgency warning was 0.94. This warning featured a continuous sound pulse of 0.107s duration interspersed with 0.007s of silence. The results reveal that the participants can not differentiate the urgency in the forward collision settings. That means the rated (perceived) urgency of the different FCW used was not significantly dissimilar ($p>.05$). But the rated annoyance differed ($p<.05$). Interestingly, the driving performance was influenced also by the kind of warning. The accelerator release time was about 325ms faster for the high urgency sound (mean 1.16s) than for the low urgency sound (mean 1.48s, $p<.05$).

Marshall et al. (2007) investigated the dependency of perceived urgency and annoyance in auditory signals for the driving context. The goal was to identify alert parameters that increase perceived urgency more than annoyance, to figure out how context affects urgency and annoyance, and to understand how alert parameters influence what is perceived as an appropriate alert in different contexts. Three experiments were conducted. The subjects listened to the alerts on headphones in a laboratory. They were not involved in any driving activity - neither in a simulator, nor in a real car. In Experiment 1, harmonic series, pulse duration, inter pulse interval, and the context of an alert were varied. Participants read the description of the scenario (not explained in the text) and then imagined hearing the alert from one of three in-vehicle systems: collision avoidance, navigation, and E-mail. The dependent variables were perceived urgency and annoyance rated on a 100-point scale or measured by paired comparison. The paired comparisons were created by combining each alert with every other alert in random order. The results show effects of all alert modifications but no effects by the scenarios or driving context. Perceived urgency and annoyance are highly dependent. But increasing pulse duration increased urgency substantially more than annoyance (cf. Tab. 2.8). In Experiments 2 and 3, the experimenters used the same equipment and interview technique. The independent variables in Experiment 2 were burst duty cycle (three vs. four pulses) and offset, onset conditions (slow vs. fast). In Experiment 3, the independent variables were alert duty cycle (percent of time of the alarm when sound is present; 20 vs. 80%), the interburst period (378ms vs. 227ms), and sound type (different frequency series). The results for Experiment 2 showed that increasing offset and burst duty cycle increased perceived urgency substantially more than they increased perceived annoyance. In Experiment 3, a low

Characteristic Effect	on Urgency Effect	on Annoyance
Pulse duration	Longer more urgent (0.80)	Longer more annoying (0.28)
Inter pulse interval	Longer less urgent (0.92)	Longer less annoying (0.62)
Harmonic series (formants)	High (a) more urgent (0.50)	High (a) more annoying (0.66)
Alert onset	Fast more urgent (0.66)	Fast more annoying (0.42)
Alert offset	Fast more urgent (0.66)	Fast more annoying (0.22)
Burst duty cycle	High more urgent (0.44)	High more annoying (0.24)
Alert duty cycle	High more urgent (1.36)	High more annoying (1.0)
Interburst period	Shorter more urgent (0.50)	Shorter more annoying (0.30)
Sound type	Frequency series more urgent (0.26)	Frequency series less annoying (-0.40)

Table 2.8: Effects of Parameters on Perceived Urgency and Annoyance. The difference in z scores is shown in parentheses (Marshall et al., 2007)

alert duty cycle and a short interburst period effected in high perceived urgency (cf. Tab. 2.8). The sound types used showed a diametrically opposed effect for perceived urgency and annoyance. Annoyance and appropriateness are highly correlated. Thus, Marshall et al. (2007) showed the possibility to design acoustic warnings which create a stronger feeling of urgency while the perceived annoyance rises at a slower rate. The authors expect to minimize the "cry wolf" effect if a warning is designed which results in low annoyance.

Speech Speech output has the advantage that it can be very precise in telling the receiver what the threat is and what is to be done. Speech is also perceived through an automatic cognitive process which is potentially more effective in stressful situations. On the other hand, most speech messages can not be understood until the message is almost complete (Graham, 1999). This reduces the possibilities of speech output for time critical warnings. Because the message has to be short, only one- or two-word messages can be used. This severely decreases the information content which can be conveyed. Additionally, RT to speech warnings are relatively slow (e.g., Kiefer et al., 1999; Graham, 1999). Speech output is not recommended for time critical applications (Campbell et al., 2007).

Auditory Icon Gaver (1986) invented the term "Auditory Icon" for naturally occurring sounds that can convey information about system events by analogy with everyday events. Optimally, these signals do not have to be learned because they have already been associated with something. Auditory icons are representational sounds. One of the best known Auditory Icons is the sound of crumpled paper which accompanies the trashing of a file on a computer desktop. Examples for Auditory Icons as warnings are the squeaking of tires to denote a braking car or a gurgling sound when the tank is empty. Sometimes the problem occurs that users do not interpret the Auditory Icon as a signal from a system.

Graham (1999) conducted an experiment where four different acoustic signals served as FCW and were compared. The signals were as follows: 1. one was a tonal signal (a beep) shaped as a 'sawtooth' function at a frequency of 600 Hz; 2. a speech warning, a female voice saying "ahead!" in a firm but calm manner; 3. auditory icon, sound of a car horn, and; 4. auditory icon, sound of skidding tires. The loudness level for all sound was about 60db(A) and all sounds lasted for 0.7s. The participants were seated in a kind of simulator. The car was a real car but the scenery was a compilation of recorded video clips of traffic scenarios shown over a projector. The video clips contained harmless situations and forward collision threat scenes. All threat clips were stopped and frozen at TTCs of 2s. The warnings were given out 1.4s before the freeze. On the dashboard of the simulator a small LCD display was mounted. The participants had to accomplish a tracking task on this display. The participants were told that the tracking task was their main task and whenever they heard a warning they should look at the road scenery and decide if a crash was imminent. If this was the case, they should use the brakes of the mock up immediately. The results show significantly faster reaction times for the auditory icons. The mean BRT was faster for the horn (mean BRT = 0.74s, SD = 0.18s) than the tone (M = 0.81s, SD = 0.19s) or speech (M = 0.86s, SD = 0.21s) warnings, and significantly faster for the tire-skid (M = 0.75s, SD = 0.23s) than the speech. In the auditory icon conditions, participants produced significantly more false alarms, which means that they used the brake in a harmless situation. A subjective ranking revealed that the subjects rated the appropriateness of the sound in the following descending order: 1. car horn, 2. tire skid, 3. speech, and 4. tone.

Belz, Robinson, and Casali (1999) conducted a simulator study on auditory warnings for front and side collision avoidance systems in commercial trucks. They focused on the use of auditory icons. Twenty-four male truck drivers participated in the experiment. For the front collision avoidance system the study used a three way, within subject design with the following independent variables: (a) display presentation mode (no display, dash-mounted visual display only, auditory icon only, conventional auditory warning only, mixed-modality 1 [auditory icon and dash-mounted visual display], or mixed-modality 2 [conventional auditory warning and dash mounted visual display]), (b) vehicle speed (56 or 88 km/h), and vehicle headway (2.5 or 3.5s). The dash-mounted display is shown in 2.23. Depending on the threat, the appropriate trapezoid flashed intermittently at a rate of 2 to 4Hz when activated by critical headway. The conventional tones for the FCW consisted of four pure tones at 500, 1000, 2000, and 3000 Hz presented concurrently during one pulse of 0.35s. For the side collision warning a 'sawtooth' waveform at 500hz was used. The auditory icons used were the sound of skidding tires (FCW) or a car horn (SCW). All warnings had a total du-

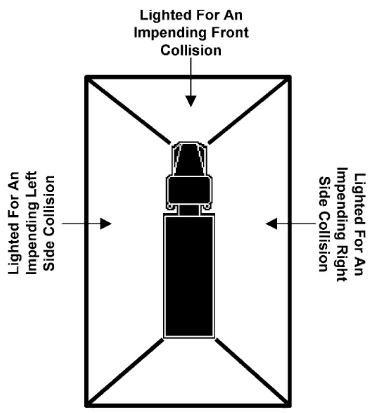


Figure 2.23: Dash-mounted display (Belz et al., 1999)

ration of 0.7s. The sound level of the warning sound exceeded the noise by at least 13dB(A). The results show significant differences in break reaction times. In the FCW situation, the auditory icons (and combinations with AI) resulted in shorter BRT (approx. 830ms BRT) than the conventional auditory warning and no warning at all (approx. 1000ms), and the visual only was significantly slower than the rest (1221ms). In the side collision situation, participants had significantly ($p<.05$) fewer accidents with the AI than with the conventional tonal warning. This difference increased when the visual warning was added. There is a clear preference by the participants for the combination of AI plus visual warning in the FCW condition.

Haptic Warnings

Haptic Warnings are displays that are *felt* through tactile, vestibular, or kinesthetic sensations and perceptions. Haptic Warnings' advantages are the following: the recipient does not have to look in a certain direction, they are discrete (the passengers do not realize it), fast reaction times (see Fig. 2.6), and the possibility to guide action. The major disadvantages are that the warning device has to be touched and the possibility of misinterpretation. Here the same thought applies as for the auditory warnings. According to the multiple resource model, a cross-modal task and information presentation should lead to more efficient processing and improved task-sharing performance. Therefore, the visual main task (driving a car) should be less compromised by a haptic (or auditory) warning than a visual one (Wickens & Hollands, 1999, chapter 11). In aviation, tactile warnings have been established for a long time. Examples for that are the stick-shaker that indicates proximity to a stall, the foot-thumper which indicates cycling of the anti-skid system, and the stick-pusher which assists the pilot in reducing the danger of a stall.

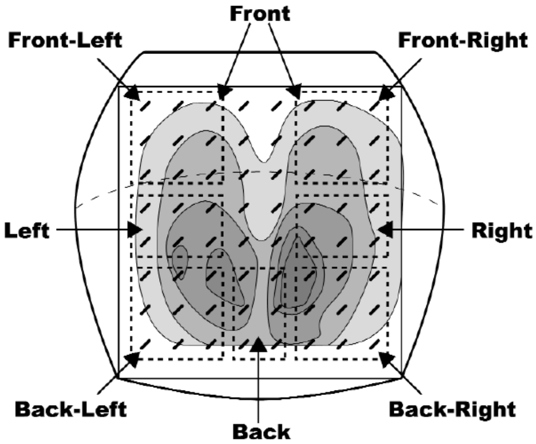


Figure 2.24: Seat vibration actuators location and seat pan pressure distribution plot (Fitch et al., 2007)

It has been shown several times that haptic warnings are a good solution for drawing someone's attention to, for example, a monitoring task (e.g., Hopp, Smith, Clegg, & Heggestad, 2005). Ho, Tan, and Spence (2005) showed that a vibration applied to the torso ventral or dorsal is able to facilitate the detection of visually displayed information. This was especially true for information in front of the subjects combined with ventral vibration and displaying something behind the subject plus a dorsal vibration.

Similar insights were found by (Fitch, Kiefer, Hankey, & Kleiner, 2007) who conducted a in-traffic real car study with auditory and in-seat vibration warnings. Eight directions had to be detected by the participants (see Fig. 2.24). Each alert was played for 1s with 100ms ON and 100ms OFF cycles. The auditory alerts were played though 4 speakers in the corners of the car's cabin. Right, back-right, and back-left were generated by playing the alert sound on either the front-left, front-right, back-right, or back-left speaker. The four cardinal alert locations (front, right, back, and left) were generated by playing the alert sound simultaneously on two speakers using the phenomenon of summing localization. The auditory alerts were balanced to 75dB(A). Two broadbent sounds were used, a higher pitched for the front-left, front, and front-right locations, whereas the lower pitched broadband sound was used for the other locations. The directional haptic seat alert approach involved triggering seat vibrations that were generated by an 8×8 array of pager vibrator motors in the seat cushion. The directions were indicated by using 3×3 array in the respective corner of the seat as shown in Fig. 2.24.

The within-subjects variables examined were directional alert type (auditory, haptic seat, haptic seat and auditory, and haptic seat and non-directional auditory) and alert location. The participants drove on a pub-

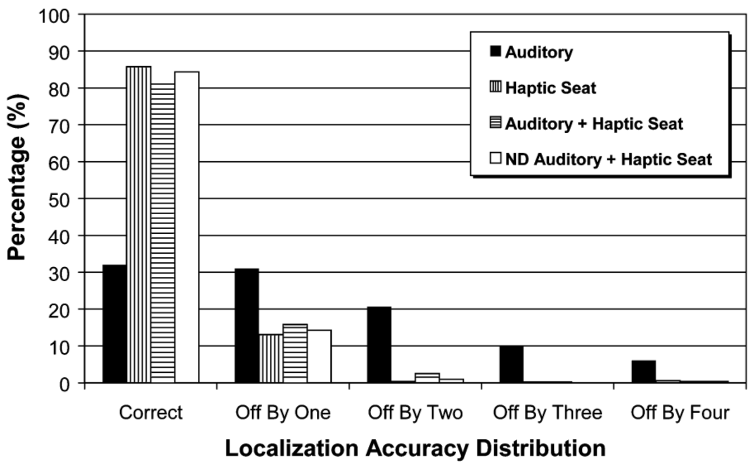


Figure 2.25: Distribution of the degree of correctness of localization responses as a function of directional alert type (ND = non-directional) (Fitch et al., 2007)

lic highway at approximately 88 km/h. Percentage correct localization for auditory, haptic seat, haptic seat and auditory, and haptic seat and non-directional auditory alert approaches were 32%, 86%, 81%, and 84% (cf. also Fig. 2.25. All conditions with the haptic display produced clearly better detection rates than auditory alone.

In a flight simulator study, Sklar and Sarter (1999) showed the superiority of haptic warnings over visual warnings when the situation being warned of could go by unattended. Twenty-one flight instructors were trained on a flight simulator. There were three kinds of warning that had to be detected. The participants received them either visually, tactilely or in a combination. The tactile warning was a vibration displayed by a motor on a wrist band the participants wore. The detection rate was close to 100% in both the tactile and the combined condition, while it was 83% for the visual only condition. This difference is significant ($p<.001$). The reaction times were also faster for the tactile and tactile plus condition. This result promotes the advantage that a tactile stimulus cannot be missed if it is assured that the recipient is in touch with the warning device.

Tijerina et al. (2000) conducted three studies concerning haptic warnings for rear end collision situations. The first two studies were pilot studies to investigate the specifications of the warning. The two warning candidates were a mono brake pulse and a steering wheel vibration. Six participants took part in these studies. They revealed that a warning by the steering wheel is not associated with a braking situation and thus not recommended. The mono brake pulses investigated were created by linear ramps of deceleration based on all combinations of three jerk rates (0.08 g/s, 0.20 g/s, and 0.32 g/s) and three durations (0.25s, 0.65s, and 1.0s). The task of the participants was to notice the brake pulse and then bring the car to a full stop. They were either distracted by a navigation system entry or not. There was no lead vehicle. Tijerina et al. (2000) analyzed detection performance, accelerator release time, and subjective ratings of appropriateness. The results showed that the combination of a brake force of 0.32 g/s linearly ramped up for 0.65s is the most promising brake pulse for a FCW application. The results indicated that the magnitude of the pulse braking display had a consistent impact on the magnitude of the driver's braking response. A higher jerk rate and a longer braking pulse duration lead to a harder breaking response by the driver. The authors consider using these parameters to influence the driver's situation-dependent behavior. In the third study, seven participants followed a confederate car on a test track. The confederate car towed a simulated end of a car that had the braking lights disabled. The participants followed at 72 km/h (45mph) and with a 2s time distance with an enabled ACC. The lead vehicle braked with 0.35 g nominal. The brake pulse warning was initiated when the TTC fell below 25s. The authors wanted to be sure that the warning was issued before the subject's braking response. The participants were instructed that they were responsible for bringing the vehicle to a safe stop if the lead vehicle braked although they were driving with an ACC. The subjects experienced 8 practice trials without the warning to become acquainted to the car's brakes and the ACC braking behavior. After that, 24 test trials were completed, of which 9 included true alarms, 9 false alarms and 6 correctly without any alarm. Tijerina et al. (2000) combined 3 jerk rates (0.08, 0.20, and 0.32 g/s) with 3 durations (0.25, 0.65, and 1.00 s). The results show that the participant's brake force is determined by the trajectory of the two cars and not by the brake pulse parameters. For the true alarms, the participants braked in every situation - sometimes even before the warning. But the warning was not noticed every time. For the short warnings, just 2 out of 7 warnings were noticed. The long and strong warnings were noticed 5 out of 7 times. In the false alarm condition, on the other hand, all combinations (except the 0.08g/s plus 0.20s) were noticed at least 6 out of 7 times. Also, in the false alarm conditions there were inappropriate relations. This means in 20 of the 63 false alarm situations a participant braked unnecessarily. Again it was found that the harder the brake pulse the harder the subjects braked. But none of these events included hard braking. The authors conclude that a mono brake pulse can be used for a FCW but should be tested on a long term basis and, in addition, with other modalities.

A haptic back display was investigated by H. Z. Tan, Gray, Young, and Traylor (2003). They mounted 9 tractors in a 3×3 array on the back rest of an office chair. Each inter-tractor spacing was 8cm. The participants had to observe visual scenes and detect changes on the display. The used bursts consisted of different ON pulses (80, 480, or 800ms) and OFF pulses (fixed at 120ms). The subjects had to sit with their back pressed to the back rest of the seat. The results show that the reaction time was faster with the vibration (2445ms) than without (4075ms). In a follow-up study, haptic directional cuing was investigated. The spatial information of where the change takes place is coded in the sequence of the tractors vibrating. For example, to display the direction north (or up), first the middle-low, then the middle-middle, and finally the middle-high tractor vibrated (3 pulses each). This was called a thin line. The example for north with a thick line would be first all low, then all middle, and then all high tractors. The subjects detected each direction with more than 80% correctness.

Erp and Veen (2004) compared haptic with visual navigation information in a driving simulator. Visual and tactile symbols were made for three distances: 250, 150, and 50 m. Distance was indicated alphanumerically for the visual symbol, and by vibration rhythm for the tactile symbol. Tactile information was given through four tractors in the seat placed under the thighs. The visual symbol was an arrow plus numeric distance indication. The haptic display always consisted of multiple bursts of vibration with a burst length of 60 ms. The 250 m information consisted of three bursts separated by 270 ms in time. The 150 m and 50 m were designed as sweeps, that is multiple bursts separated by decreasing intervals. The 150 m information consisted of six bursts with intervals decreasing from 270 ms to 60 ms. The 50 m information consisted of five bursts with intervals decreasing from 60 to 10 ms. The participants had to follow the navigation instructions and were instructed to use the turn indicator immediately when they received a navigation instruction. A between subject variable workload was implemented. The subjects either had to accomplish a secondary cognitive task or not. The presented modality (visual, haptic, and multi modal) was an in-between factor. The results show that the subjects rate the tactile display as the least cognitively demanding. There is a significant difference ($p<.05$) in the RT for the visual vs. the multi modal display whereas the multi modal is faster. The RT for the peripheral detection task was not significantly different. But there was a tendency ($p<.08$) for the RT in the visual condition plus the high workload condition to be longer than in the other conditions.

Lee, Hoffman, and Hayes (2004) implemented a FCW in a fixed-base simulator. They compared haptic (seat vibration) and auditory warnings (tone, not further specified) as well as graded vs. one-step warning strategy. The 40 participants followed a lead car which stopped unexpectedly in a way that was considered either negligible, moderate, or severe. According to the braking condition, the warning was more intense (auditory: 53.7, 62.5, or 74.3dB; haptic: not specified). All warnings were accompanied by a visual warning in a high-head down display which showed a collision icon. In contrast to other studies, the results revealed no driver response differences due to the warning modality. The drivers adapted their braking behavior to the level of threat.

Forward Collision Warning System Timing

The question of System Timing seeks the answer to under which physical conditions should the system trigger a warning. This is an essential question to be asked in FCW design. Not only that a warning that comes too late could lead to an accident and make the whole system useless, an early warning raises the probability of annoying the driver because too many warnings are issued. Furthermore, system timing is a big factor for user reliance and compliance as pointed out in Section 2.2.4.

There are several approaches to defining the physical conditions. A very common way is to calculate the Time-To-Collision (TTC) and define a warning threshold. This approach is often used in the above cited experimental settings. These experiments are usually concerned with warning design. When system timing is the focus area, more sophisticated algorithms are applied. One algorithm often reported in the literature is the Stop Distance Algorithm (e.g., Abe & Richardson, 2004; Brouwer & Hoedemaeker, 2006; ISO, 2002; Jamson, Lai, & Carsten, 2007; Kiefer et al., 1999). The stop distance algorithm takes the preceding and subject vehicle's absolute speed and deceleration and calculates both stopping distances plus a distance for brake reaction time of the ego vehicle. The subtraction of both distances is compared with the warning distance and, if exceeded, the driver is warned (cf. Eq. 2.10). Usually the subject vehicle deceleration (a_{ego}) is assumed. This value depends on the assumptions made by the system designer. This formula is not exhaustive. If, for example, the lead vehicle comes to a halt, the equation is not applicable.

$$D = V_{ego} \cdot T_{BR} + \frac{V_{ego}^2}{2 \cdot a_{ego}} - \frac{V_{pre}^2}{2 \cdot a_{pre}} \tag{2.10}$$

D	is the distance to preceding vehicle (obstacle)
V_{ego}	is the subject vehicle speed
V_{pre}	is the preceding vehicle (obstacle) speed
T_{BR}	is the free running (driver's brake reaction) time
a_{ego}	is the subject vehicle deceleration
a_{pre}	is the preceding vehicle (obstacle) deceleration

Another approach is the modeling of driver behavior in reference to last second braking as reported earlier in section 2.1.6 (Kiefer et al., 2005). Here experimental real car data is the basis. To calculate the time of warning Kiefer et al. (2005), take the point of last second braking and add an estimated driver reaction time (cf. equations 2.2 to 2.4). And another assumption is made. The driver is braking with a certain force derived from the test track data. In every approach to find the right time to issue a warning, assumptions about the driver behavior have to be made.

Unfortunately, hardly any article gives precise information about the physical conditions when a warning is issued. Most information is given in the article by Kiefer et al. (2005). Most articles only state that an "early" and a "late" warning were compared. In the related articles, participants showed a better performance with the early warnings (e.g., Abe & Richardson, 2004; Lee, McGehee, Brown, & Reyes, 2002). That means they avoided more collisions and the minimum TTC was larger. This result was expected but may be limited by the fact that drivers who were confronted with a FCW system for a longer period of time might declare the early warnings as unnecessary warnings.

One possible solution could be the idea of an adaptive FCW. Unfortunately, very little research has been done in this area. The Brouwer and Hoedemaeker project conducted experiments in this direction. Three driving simulator studies were conducted. The systems adapted to slippery road surfaces (dry vs. wet), driver distraction (distracted vs. non-distracted) and driver traits (sensation seeking, preferred following headway, and individual brake reaction time). The adaption to road surface lead to safer behavior when the system worked adaptively. At the same time it was also more irritating, i.e., less easy for drivers to learn. This result is confounded by the fact that the non-adaptive system used the dry road configuration only. In the second experiment where the system adapted to driver distraction, no differences were found. The authors explain this with poor effort on the distraction task. The third experiment also did not reveal differences for the adapted system. Interestingly, the participants with the short preferred headway reacted faster to the threats than the other subjects.

Short Summary

The research so far has shown that FCW change the driver's behavior in a positive way. Drivers react faster and hence avoid more collisions with these systems than they would have without. For the experiments, a focus lay on distracted drivers who are the main cause for fatal crashes. When the research interest lay primarily on the differences of special warning solutions, often no threat at all was used.

Regarding reaction times, visual displays produce the slowest results in comparison to acoustic and haptic solutions. Nonetheless, they are often used as an additional modality. They are especially useful for continuous information or for explaining alarms. Luminance, color, and position have been investigated often. Size was not found to be systematically changed. The major advantages of acoustic warnings are that they can be perceived independent of head position and attention focus and the perceived urgency can be modified well. Reaction times with acoustic stimuli are short, but the localization is often not satisfying. Two studies showed the superiority of Auditory Icons over pure tone warnings regarding reaction time, but the perceived urgency was not regarded. Further Auditory Icons have the problem that they can be mixed up with real world sounds and thereby do not clearly indicate that they are a warning. Haptic warnings elicit fast reaction times and the subgroup of tactile warnings have been shown to display a direction dependably. The study by Lee et al. (2004) showed no modality differences between seat-vibration and acoustic warnings, but a dependency of the reactions to the experienced threat.

System timing is under research and shows that earlier warnings lead to safer situations. The approach by Kiefer et al. (2005) incorporates Human Factors research and derives a warning timing from human behavior under attentive conditions. Approaches regarding the stopping distance work in reverse and add a reaction time to the physically needed braking reaction. As the different timing algorithms are in production for only a relatively short time, advantages of one approach have not been proven.

2.4 Classifiction of reactions

In the area of collision avoidance research, actions by the participants and the warning system have to be classified in reference to each other. As a lookout on the experiments presented in this work, here a system for classification is proposed.

The Signal Detection Theory (SDT) (D. M. Green & Swets, 1966) is often used when classifying reactions by systems or humans to signals (see also section 2.2.4, page 37). But the analysis of avoidance reactions (i.e., braking) and warnings – at least in the domain of collision avoidance – always excluded the parallelism of perceiving the environment by the human and the system. The focus lay either on the system or the human detecting the hazard or solely on the human detecting the alarm. In a lot of the introduced experiments this was achieved by forcing the participants to look away from the street (e.g., Graham, 1999; Lees & Lee, 2007; Lind, 2007). Driver behavior tested with this methodology reflects only a minor sample of scenarios from traffic. In order to analyze a wider variety of real world scenarios, this is not enough. A driver can and, in most cases, will react prior to/without a warning.

A step in this direction is the work of Sorkin and Woods (1985) that was introduced on page 37. They enhanced the SDT with the idea of serial processing of the system and the receiver. But still, the driver in this approach has to rely on the warning and is not able to detect a threat by himself.

For a complete analysis and classification of reactions with a warning system it is necessary to regard the following three dimensions at once.

1. Presence of a hazard
2. Presence of a warning (from the system)
3. Presence of a reaction (from the human)

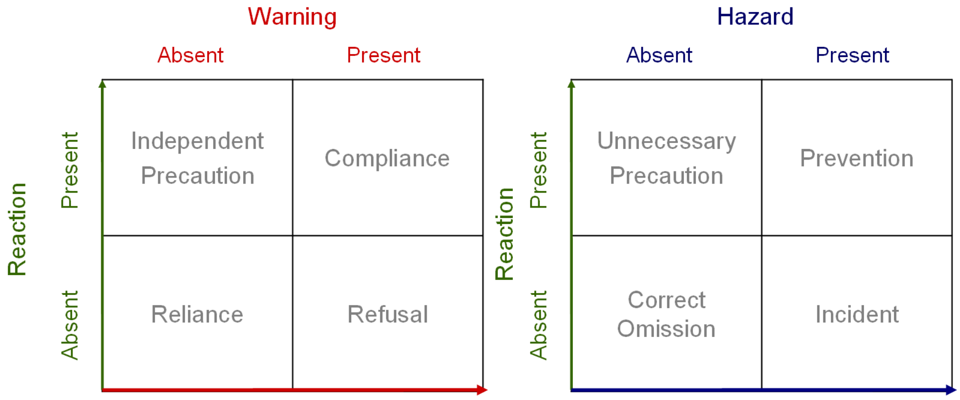


Figure 2.26: Signal Detection Theory (new applications)

Combination	Hazard	Warning	Reaction
1	+	+	+
2	+	+	–
3	+	–	+
4	+	–	–
5	–	+	+
6	–	+	–
7	–	–	+
8	–	–	–

Present (+), Absent (–)

Table 2.9: Eight possible combinations in 3D-SDT for warning systems

This approach is built up from two separate views: the combination of "Warning & Reaction" and "Hazard & Reaction" as shown in Fig. 2.26. Up to now, the notation for the "Warning & Reaction" combination usually has been the same as in the classic SDT (e.g., hit, miss, false alarm and correct rejection). A new notation is proposed as depicted on the left side in Fig. 2.26.

Combining these two two-dimensional structures to one 3D approach allows a judgment about the whole system (see Fig. 2.27 and Tab. 2.9). Enhancing the SDT to the new 3D-model can illustrate possible outcomes in an easy way. The human operator may react to the hazard in the environment and/or the warning of the system. Eight combinations are possible, as shown in Table 2.9. No matter if the operator is able to monitor the environment, these eight distinct outcomes are interesting from a theoretical point of view. With this set-up, a view on the combined performance of the system warning and human is possible. The proposed categorization of reactions will later be used in this work to sort experimental results with warning systems.

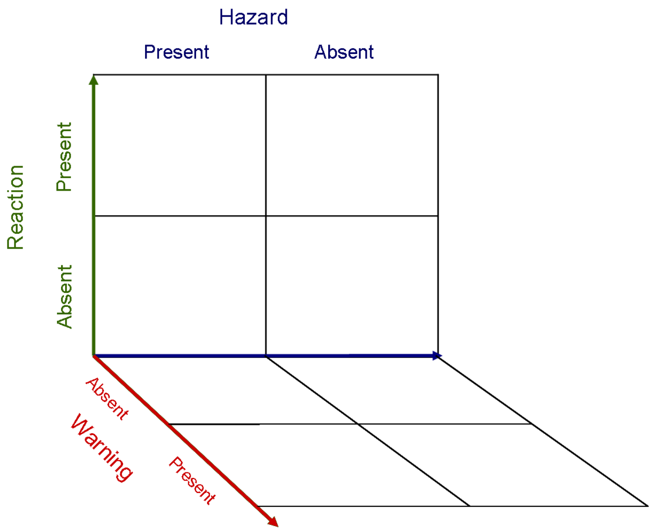


Figure 2.27: 3D Signal Detection Theory for warning systems

Chapter 3

Development of Research Question

As described in the preface, many drivers report being alert or to have been looking out of the front windshield before the crash. Therefore, the questions have to be raised:

1. What leads to the lack of collision avoidance behavior?
2. Which kind of warning could help?

To answer these questions, this thesis addresses driver threat perception and dynamic warning systems, namely FCW systems. But the research in the current literature does not provide a process model for this special issue. The models at hand miss parts that explain the context. The basic communication model (Shannon & Weaver, 1963), as described on page 34, does not provide any reason to send a message. In the same section, the model of Rogers et al. (2000) is described. It describes the internal process of the receiver, but also misses parts of the environment in which the scene takes place. The Situation Awareness model by Endsley (1995) considers the environment and implements a feedback loop from the operator to the environment, but does not include details about a system (see page 8). Derived from these influences, an additional model is proposed (cf. Fig. 3.1). This block diagram does not claim to be exhaustive, but it offers a good opportunity to assort and organize the questions of this thesis.

The proposal, as presented in Figure 3.1, has two main blocks: a system and a human receiver. The major steps in a system and a human are believed to be comparable and hence have been illustrated in a similar manner. To explain the system with a simple example, one can imagine a smoke alarm, which has been used earlier. In the environment is a fire that produces smoke. The smoke alarm is the system. The smoke detector (environmental sensor) detects smoke particles in the air. The analysis of the process reveals a value above threshold. As a result, the system performs an action, which

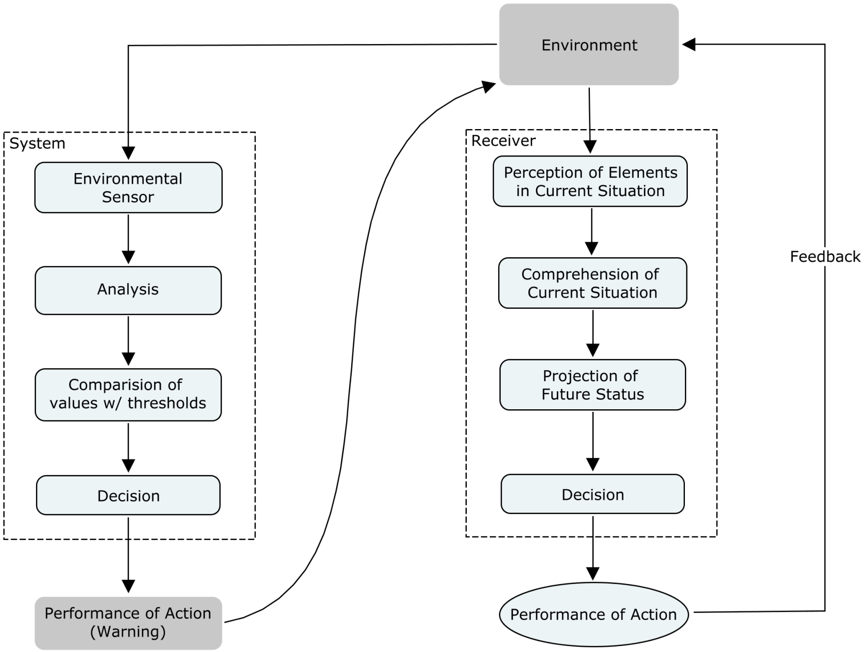


Figure 3.1: Process Model for Dynamic Warnings

then is part of the environment. In this case, it gives out a warning. The warning is an auditory signal from several loudspeakers at a certain decibel level (properties [modality, intensity, and position] not shown in the diagram). A person (receiver) in the building hears (perceives) the sound. He encodes the sound burst pattern and understands (comprehends) that this auditory signal is a smoke alarm. He anticipates (projects the future status) that the house is on fire, decides to leave, and leaves the building (decision and action). Leaving the building does not influence the system. If he would have decided to extinguish the fire, the behavior would have influenced the environment and stopped the alarm. Of course, the system could also have started a water spray system and changed the situation directly, but, as this thesis does not deal with autonomous acting systems, the second step via the receiver is shown in the block diagram. What is different in this system than in the model of the two step system by Sorkin and Woods (1985), presented on page 37 et. seqq.? The Receiver is able to detect the threat himself – independent of the system (direct link from the environment to the driver).

From this model and the theoretical background, the research questions can be derived. It can be assumed that an attentive driver is in a high workload situation when a crash is imminent and, as depicted in Figure 3.1, the warning acts as additional information in the environment. When the system is new to the driver, he might not know the alarm. For this combination, the question of whether or not the warning is a help for the driver is raised.

> Does an additional stimulus, as a warning, facilitate crash avoidance behavior in an attentive driver?

As the warning is an artificial stimulus, it might have to be learned to enhance the situation assessment in a positive way. The second step in the receiver, the "comprehension of the current situation", might not be any better with the warning in the first trials.

> Are there differences in reactions and subjective judgment to the warning between a first surprise trial and a later occurrence?

Most FCW systems analyze the situation based on a few parameters. Main inputs are the relative speed and difference to the object in path. These parameters are calculated to the Time To Collision (TTC), which represents the system's anticipation (see also section 2.3). The system assesses the situation more or less based only on *current* values. On the other hand, human situation assessment and anticipation take into account the development of a situation.

> Does the emergence of a situation influence the anticipation of the driver?
> Might a wrong anticipation be a cause of missing crash avoidance behavior?

What happens if the system develops a different situation assessment than the driver? This may result from different "sensors", different parameters that are analyzed, or a different "comprehension of the situation". All these factors could result in a different top-down attention allocation.

> Does a warning help more in situations with congruent or incongruent comprehension of driver and system of the situation?
> Could a warning compensate a wrong anticipation?
> Does the effectiveness of a warning differ if a hazardous object has been part of the scene for a longer time or if it appears suddenly?

Last but not least, there is the question of the type of warning. The warning can have different modalities and intensities. Even for the small domain of Forward Collision Warnings, many different warning types are sold on the market today.

> What influence does the design of the warning itself have on the complex interactions brought up before?

To answer these research questions, a two step approach is used. First, the warnings will be studied separately (see 4). This investigates the warning type on the driver without the influence of a situation. Here, subjective assessments and objective brake reactions to different warning intensities and modalities (visual, haptic, audible) are studied. With this knowledge, a further experiment is planned to answer the main questions of this thesis (see 5). In a driving simulator, a subset of warnings from the first experiment will be presented in several critical scenarios. The scenarios are created to allow the participant different levels of threat anticipation. The driver's avoidance behavior is analyzed under the controlled interaction of warning type and level of possible threat anticipation.

Chapter 4

Study One: Warning Modality and Intensity

To avoid a crash, a driver has to anticipate a collision of his vehicle and another object or person. A Collision Warning System shall provide the driver with information to support him in the collision avoidance process. A good Forward Collision Warning should assist the driver in a way that it informs him quickly about the imminent situation. Therefore, it is thought to enrich the driver's perception and aims to change his anticipation or, in terms of the Situation Awareness Model, aims to alter the driver's "Projection of the future".
If this is the main goal of a warning, it should have two key results for the driver:

1. Convey a high urgency
2. Elicit a fast response

Therefore, the goal of the first experiment is to investigate the possibilities of in-car warnings to fulfill the stated elements. Five possible in-car warning devices will be compared. It has been shown before that different modalities elicit different RT. This work aims to compare devices that are in production or similar to production solutions. Of special interest is the effect of varying the intensity of each warning type. As known from basic research, signals with higher intensities lead to faster reaction times (Wickens & Hollands, 1999, p. 339). If so, this would implicate a certain "operating range" of each warning actuator. The warnings will be varied in a way to see the possible differences regarding the reaction times and perceived urgency for these devices. A statement about suitability about a warning modality only would not be sufficient. Used intensity would be of major importance.
As it is known that the driving situation dominates the driver reaction over the differences elicited by the warning (e.g., Lee et al., 2004), this experiment will intentionally remove the threat with the occlusion technique. Therefore,

the pure effects of the warnings will be measured. Furthermore, the different possibilities of the actuators can be compared and then used in the follow-up experiment.

4.1 Research Questions

The questions that are addressed by this study are

- What influence do different warning types (modalities) have on driver behavior?
- What influence do different intensities of the same type of warning have on driver behavior?
- How do subjective judgments about the warnings depend on modality and intensity?
- Are subjective judgments and overt behavior correlated?

The last two items may be as important as the first, because, if a warning's primary goal is to support the driver's anticipation, the subjective urgency rating of the warning is essential.

4.2 Methodology

In this study, attention is focused on minimizing the influence of any factors other than warning modality and intensity. To identify statistical relevant influence of the independent factors on the dependent factors, analysis of variance (ANOVA) for repeated measures (e.g. Turner & Thayer, 2001) will be used.

4.2.1 Simulator

The study was conducted at the Würzburger Institut für Verkehrswissenschaften in a driving simulator called the "motion chair" that is depicted in Figure 4.1. The motion chair driving simulator was constructed using a Stewart platform motion system (hexapod) manufactured by RexrothHydraudyne. The system contains 6 hydraulic actuators, has 6 degrees of freedom and is able to move loads of up to 325 kg freely. The mock-up is equipped with measuring technology, allowing it to record driver input at a high resolution. For instance, the steering wheel angle can be measured with an accuracy of 0.1 at an update rate of 100 HZ. The EPS steering system (from the ZF company) of the mock-up is modified so as to yield realistic automobile steering behavior with respect to speed and steering parameters. In addition to the possibility of modifying the manner in which the simulator

Figure 4.1: Mock-up

Figure 4.2: Mock-up displays

treats steering before the simulation drive begins, it is also possible to dictate (virtual) steering torque from the outside. This can be achieved with a transmission rate of up to 500 Hz. The measuring technology of the mock-up is constructed in a modular fashion, so that it is possible to integrate into the system measurement of parameters, such as pulse frequency, in addition to the input necessary for modeling driving dynamics. As shown in Figure 4.2, the mock-up is equipped with three displays. Two displays are mounted behind the steering wheel and are used to show the dashboard instruments (e.g., speedometer and revolution-counter). The third display, mounted on the dashboard, was used to present visual warnings. This display was set approximately 7° below the eye ellipse centroid projection line and 15 ° right of the driver centerline. The participants wear a headset to hear the simulated acoustic environment (e.g., engine noise, wind noise, etc.), the warnings, and to communicate with the investigator. The driving simulation software that was used is "SILAB Version 2.5" (Kaussner, Grein, Krüger, & Noltemeier, 2001).

Driving Scenario

The simulated scenario was a two-lane rural road and had no curves. An example screen shot is shown in Figure 4.3. There was no oncoming traffic. The speed limit was 80 km/h. The simulator software was programmed in a way that the EGO vehicle could not drive faster than 80 km/h. When the EGO car reached the speed of 80 km/h, any position of the accelerator pedal greater than zero would keep the 80 km/h constant. Nonetheless, the participants were instructed to always press the accelerator pedal to the ground. This ensured that the distance for the participant's foot from accelerator to brake pedal was the same for all participants in every situation. When the

Figure 4.3: Screen shot rural road

EGO vehicle reached 80 km/h, it took about 30s until a simulated second car appeared 55 m in front of the EGO car. The preceding car immediately accelerated and drove at the same speed as the EGO vehicle 50 m in front of it. After following the preceding car for 280 m, 340 m, or 412 m, the vision was occluded by blackening the screen for 3 s. In 50% of the cases, a warning was presented in addition to occluding the driver's vision. The onset of occlusion and the warning happened simultaneously. When the screen showed the scenery again, the preceding car had vanished.
As was pointed out in Chapter 2, a depiction of a threat influences the driver more than the warning, because behavior is adjusted to the environment. Therefore, threat simulation was avoided in order to measure the pure behavioral effects of the warning variables. Every warning was displayed when the screen was black. The participants had to rely on the warning as their source of information. This should have maximized the warning effect. To achieve this, the preceding car merely symbolized a potential danger.

4.2.2 Warnings

The warnings were chosen to represent stereotypical warning types for modern Advanced Driver Assistance Systems (ADAS). Five types of warnings in two intensities (low vs. high) were used in this experiment. The used warnings were

- Visual high-head-down display,
- In-seat vibration,

Figure 4.4: Visual Warning Low Intensity

Figure 4.5: Visual Warning High Intensity

- Steering wheel vibration,
- Auditory tonal signal, and
- Brake pulse.

Visual Warning

The visual high-head-down display was mounted on the dashboard of the simulator at a place where the front windshield would meet the dashboard (cf. Figure 4.2). It had a display diagonal of 7 inch. The distance to the participants' head varied because the participants could adjust the seat to their body height as in a real car. The warning was a flashing red icon on the display. The 2008 General Motors Forward Collision Warning symbol was used. The intensity was modified by the size of the illuminated area. The low intensity warning used the FCW icon only (see Figure 4.4) whereas, in the high intensity condition, the icon was surrounded by ten red squares (see Figure 4.5). If there was no warning presented, the screen of this display was black. For a warning, the symbols were presented for 1s with a 50% duty cycle and a 100ms off/off period.

In-seat Vibration Warning

As shown in the two figures, 4.6 and 4.7, the seat of the driving simulator was an original 2006 *Opel Vectra* seat equipped with the four in-seat actuators. In the photo, the positions of the four haptic sensation generators (HSGs) are marked with white stickers in Figure 4.7. With the help of the driving simulation software SILAB, it is possible to control the amplitude and duration of the HSGs. The intensity of the effect is controlled by varying the speed of the DC motor, which is mounted on a metal plate with an eccentric cam attached to the motor drive shaft. Higher motor speed leads to a greater haptic effect. Only the two front motors were used, because this is the typical method of actuation for Forward Collision Warnings, if haptic seat vibration is used. As with the visual warning, the haptic pulses were

Figure 4.6: In-seat motor installation

Figure 4.7: In-seat motor position marked by stickers

presented for 1s with a 50% duty cycle and a 100ms off/off period. The high intensity warning ran the motors with 80%, while the low intensity warning ran at 40% of the maximum speed.

Steering Wheel Vibration

A genuine Electronic Power Steering (EPS) unit was embedded in the simulator mock-up. Through this, it was possible to simulate steering thrust and additional steering momentum. The steering wheel vibration warning was a 60Hz sinusoidal momentum overlay additional to the steering thrust in the simulated driving situation. The warning lasted 900ms. 900ms was chosen because the pulsating warnings have a 100ms "Off"-period at the end. Therefore, they practically end after 900ms. The low and high intensity warnings resulted in a closed-loop additional momentum of about +/- 0.5 Nm and +/- 1.0Nm, respectively.

Audible Warning

For the acoustic warning, the same On/Off logic as for the visual and haptic in-seat warning was used: 1s duration with a 50% duty cycle and a 100ms On/Off period. The sounds used were pure sine waves. The low and high intensity warnings were a 250 Hz and a 2000 Hz sound, respectively. The sound was presented over the headphones the participant was wearing during the whole study. To ensure the frequency was the only difference between low and high intensity, the sound pressure level and the loudness were measured with a dummy head microphone. The goal was to have comparable loudness. The calibrations used are listed in Table 4.1. During the study, the headphones simulated the vehicle noise (engine, wind, chassis). The warnings were displayed additionally to the vehicle noise. The sound pressure level of the vehicle noise at the time the warnings were displayed was at about 60 db(A).

Sound	SPL	Loudness
250 Hz	85 dB(A)	24 sone
2000 Hz	80 dB(A)	24 sone

Table 4.1: Sound Pressure Level and Loudness of Warnings

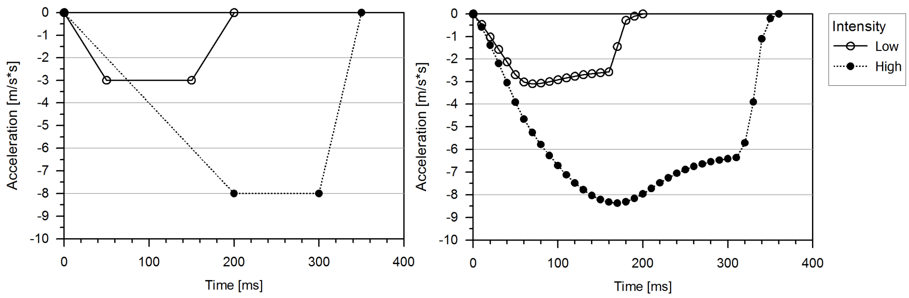


Figure 4.8: Requested (left) and measured (right) acceleration for brake pulse Warning

Brake Pulse

The brake pulse warning was realized by the 6-DOF motion platform, which the cab of the simulator was mounted on. Through this tool, the participant perceives the kinesthetic information of the simulator. The requested deceleration of the low and high intensity brake pulse is depicted on the left hand side in Figure 4.8. The measured accelerations of an open loop data collection are shown on the right hand side of the same figure. For the low intensity pulse, the requested maximum deceleration was 3 m/s^2. The demanded fade-in time was 50 ms. Then the deceleration stayed for 100 ms and was faded out in 50 ms. In open loop measurement, this brake pulse resulted in 1.3 km/h velocity loss. The high intensity warning requests 8 m/s^2 deceleration with 200ms fade-in time, 100ms duration, and 50ms fade out time. Measurement showed that this brake pulse resulted in 8.5 km/h less speed. The measured data in Figure 4.8 shows that the resulting maximum deceleration is reached earlier than requested. The gradient also shows a decay of the deceleration. This is mainly due to the hydraulic the platform is mounted on. It is only possible to display short acceleration events because the hydraulic cylinder has only a certain length it can use. Nonetheless, the difference between the two intensities is easily perceivable.

4.2.3 Study Plan

A repeated measures design with 5×2 factors is applied, which results in ten different warnings (see Table 4.2). Each warning is presented six times. The order of the warnings is quasi-randomized with the input requirement that

Table 4.2: Repeated measures study plan

	Modality				
Intensity	Visual	Seat	STW	Tone	Brake Pulse
Low	N=16	N=16	N=16	N=16	N=16
High	N=16	N=16	N=16	N=16	N=16

Table 4.3: Participants' Age Distribution

Group	Mean Age [yrs]	SD	N
Older	59.13	6.20	8
Younger	24.25	1.83	8
Older Females	57.50	6.24	4
Older Males	60.75	6.60	4
Younger Females	24.25	2.22	4
Younger Males	24.25	1.71	4

a modality shall not be presented twice in a row.

4.2.4 Participant Sample

Sixteen persons participated in this study. These people were highly trained in simulator driving. This means that they had at least a 3 hour training session which is described in S. Hoffmann and Buld (2006) and usually have participated in other simulator studies in the WIVW facilities. Half of the participants were female, half were male. The age ranged from 21 to 70 years. The participants were split into two age groups. In the younger group, the ages ranged from 21 to 33 years, whereas the older group's age ranged 51 to 70 years (see also Table 4.3).

4.2.5 Experimental Procedures

In the beginning of each experiment, the participants gave their consent for collecting demographic data, questionnaire data, and simulator data and to publish their data, when it is anonymized (cf. Appendix B, Figure B.1). After that, they filled out a form about their driving habits. Then they were informed that they would have to react to several types of warnings in the simulator. After the participants were asked to sit down in the simulator mock-up and adjust the seat, they were told about the course of events in the simulator. They were told that the simulator was programmed in such

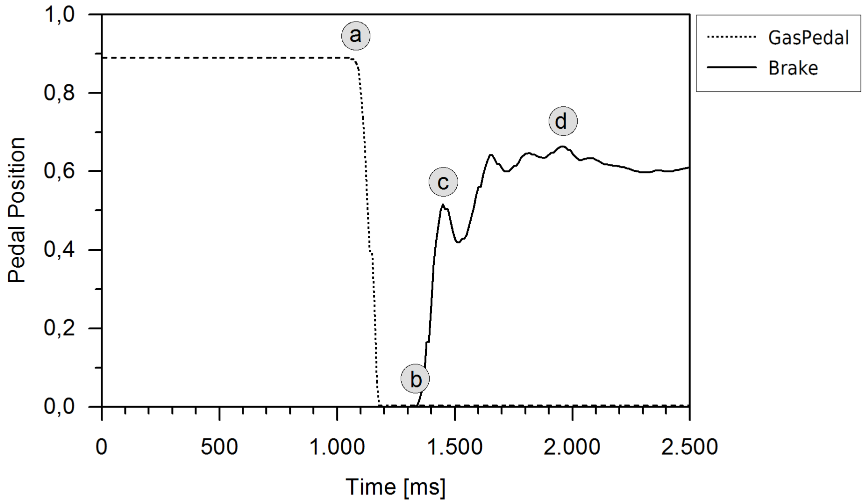


Figure 4.9: Example Plot of Gas and Brake pedal position

a way that it could not exceed 80 km/h. They were instructed to drive that speed and to press the accelerator pedal down completely at all times unless they wanted to brake. Then the experimenter started the 10 min training session, where the participants experienced the occlusion and every warning modality in the low intensity. Before every warning, they were informed what kind of stimulus would be presented. As for the main study, they were instructed to brake as fast as possible, whenever they perceived a warning but to stay on the accelerator pedal, when the black screen occurred without a warning.

After that, the main part of the study was started. The participants experienced 120 occlusions with 60 warnings in 90 min. The order of occlusions and warnings was randomized and not known to the participant. The experiment was split into two parts of 45 min each with a 10 min break. It was the driver's task to always stay fully on the gas and to brake as fast as possible only if a warning was presented. Therefore, this can be classified as a Go- / NoGo-task. The participants were not instructed how strongly they should brake, only that they should start to brake as fast as possible and always bring the vehicle to a full stop. When the EGO car stood still, the participant had to answer five questions about the warning (cf. sec. 4.2.6). After answering the questions, he was asked to accelerate the car to 80 km/h again. At the end of the experiment every participant was payed 20 € as compensation.

4.2.6 Dependent Variables

Objective Data

The objective parameters are computed from simulator raw data. Of major interest are parameters that could determine the influence of the warnings on reaction time. When a driver is pressing down on the accelerator pedal and wants to brake, one can extract different time parameters. To clarify the points in time that were analyzed, Figure 4.9 shows an example of Gas and Brake pedal position over time. The letters ⓐ to ⓓ mark important points in the plot to explain the extracted parameters. In this example at $t = 0$ the warning occurs. 1. The point in time the foot starts to move backwards on the gas pedal (at ⓐ). The duration until ⓐ will be called Gas Reaction Time or GRT. 2. The duration of the start of foot movement until the first touch of the brake (from ⓐ to ⓑ). This will be called Movement Time. 3. The point in time when the foot touches the brake for the first time (at ⓑ). The duration from the warning until ⓑ will be called the Brake Reaction Time or BRT. Trials with Gas Reaction Times higher than 2 s will be excluded from the analysis.
Furthermore, there will be analysis of whether or not the warnings have an effect on braking intensity. To answer that question, the maximum brake pedal position will be analyzed (at ⓓ). Additionally, the brake pedal's first local maximum will be analyzed (at ⓒ). It is assumed that this gives information about the subjective perception of threat information content. The velocity at the end of the occlusion will be analyzed as an integrated parameter that reflects reaction time and reaction intensity.

Subjective Judgment

After each warning event, the participants were asked five questions. The questions and answering scales were stuck at the side of the mock-up, allowing the participants to look at it while answering the questions. The questions were asked in the following order:

1. How urgent was the warning?
2. How serious was the warning?
3. How much did the warning startle you?
4. How annoying would a false alarm be once a week with this kind of warning?
5. How appropriate is this signal as a collision warning?

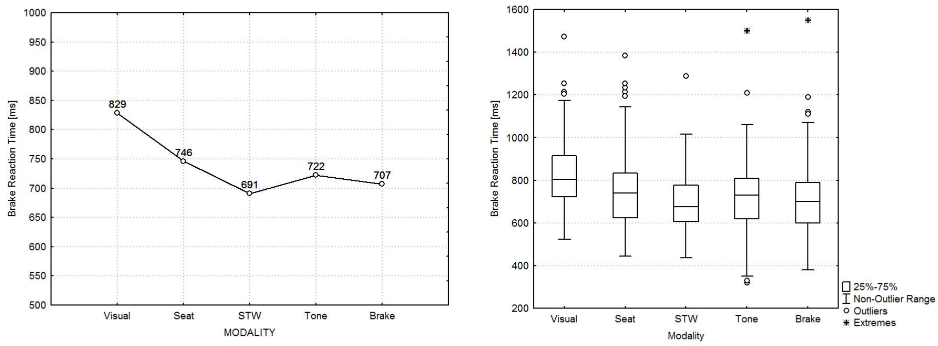
Questions 1, 2, 3, and 5 used the same answering scale with nine numerical categories from 1 to 9 and a superior verbal scale with the words *little* (1-3), *medium* (4-6), and *very* (7-9). The question about being startled also used a numerical scale with a superior verbal scale, but the numerical scale reached from -4 to +4. The describing words were *too little* (-4 to -2), *appropriate* (-1 to +1), and *too much* (+2 to +4).

4.3 Results

All parameters will be shown as boxplots split for modalities to give the reader an impression of the distribution of data. For the other factors and interactions the data is presented in mean plots. The form of the boxplots is now further described. The horizontal line inside the boxplots indicates the median. The bottom and top of the box are the 25th and 75th percentile. The whiskers represent the lowest datum still within 1.5 IQR of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. Data outside this (outliers) are depicted with a circle. If data is outside 3 IQR it is depicted with an asterix (Extremes).

4.3.1 Objective Data

As in FCW studies, the Brake Reaction Time (BRT) is the most important factor, and this section will start with the analysis of it. The data for the different modalities is depicted in Figures 4.10a and 4.10b. The boxplots show a wide spread of reaction times, from 320 ms to 1550 ms. The modalities steering wheel vibration (STW), tone and brake pulse elicit comparable reaction times with means of approximately 700 ms. The visual warnings lead to slower reaction times with a mean of 829 ms, whereas the vibrating seat is in between with 746 ms. The repeated measures ANOVA shows a significant effect for the modalities (cf. Table 4.4 for details). A post-hoc Tukey HSD test shows that the visual warnings are different from all other modalities and the seat is also slower than the steering wheel. Furthermore, there is a global effect of the intensity. Higher intensity warnings lead to faster reaction times. When looking at the interaction of intensity and modality in Figure 4.11a, an almost constant difference of approximately 50 ms is observable for the intensity in visual, seat, and the steering wheel. But, for the acoustic warning (113 ms) and the brake pulse (84 ms), the mean effect of the intensity is larger. However, the post-hoc Tukey test shows that the different intensities inside each modality are significant on a p-level of at least 0.05 except for the steering wheel, which does not show a significant intensity. The difference for intensities for the tonal warning is interesting. For all other modalities the difference in intensities was managed by physical intensity/amplitude. The acoustic warning changed the frequency but not the amplitude. For example, in E. Hellier and Edworthy (1999), the frequency is a factor that modulated perceived urgency and was thus used here. The factor Time is also significant. The post-hoc test reveals that



(a) Means (b) Boxplot

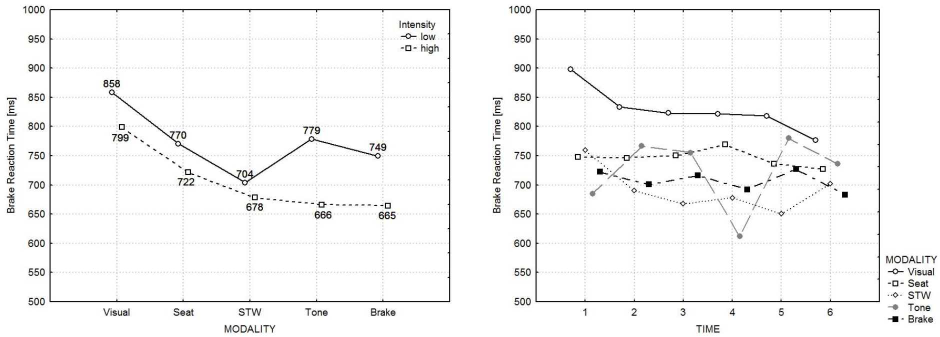
Figure 4.10: Brake Reaction Time split for Modality

only the 1st and the 4th trial differ. When looking at the interaction of Modality and Time in Figure 4.11b, it shows that this is primarily caused because half of the participants were faster than 500ms in this trial. The reaction times of the visual warning are eye-catching in this figure. It is the only warning modality that shows a constant trend, where the RTs tend to go down over time. The biggest difference occurs between the first and the second trial. One explanation is that the participants learned to observe the extra monitor after the first trial. The significant effect of the interaction of Modality and Time is primarily originated in the difference between the first visual warning and all of the other warnings. The interaction of Modality × Intensity × Time stems from the difference of the first visual warning (being slow) against the forth acoustic warning (fast). Thereby, the fast reactions in the 4th acoustic warnings are inexplicable.

Table 4.4: Repeated measures ANOVA for BRT

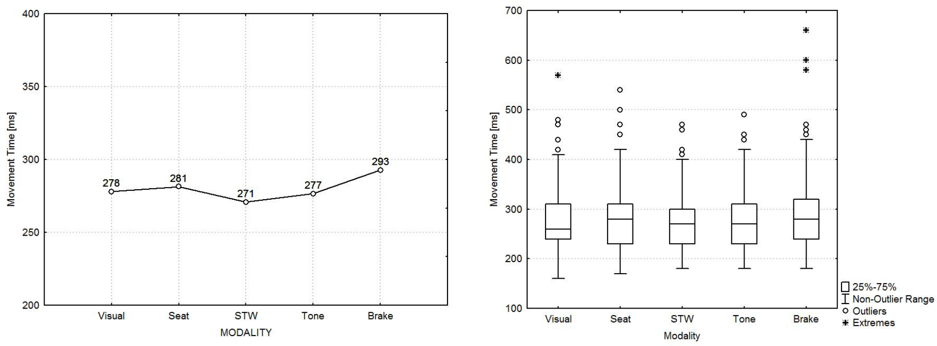
	SS	df	MS	F	p
Modality	2098201	4	524550	18.38	0.000
Intensity	988169	1	988169	79.63	0.000
Time	215506	5	43101	2.43	0.043
Modality×Intensity	202376	4	50594	5.43	0.001
Modality×Time	907804	20	45390	3.70	0.000
Intensity×Time	128717	5	25743	2.03	0.085
Modality×Intensity×Time	795012	20	39751	3.31	0.000

As expected in this study, the point in time when the participants released the accelerator pedal was very similar to the BRT, but with an offset. The statistics from the repeated measures ANOVA, including the



(a) Means split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.11: Brake Reaction Time



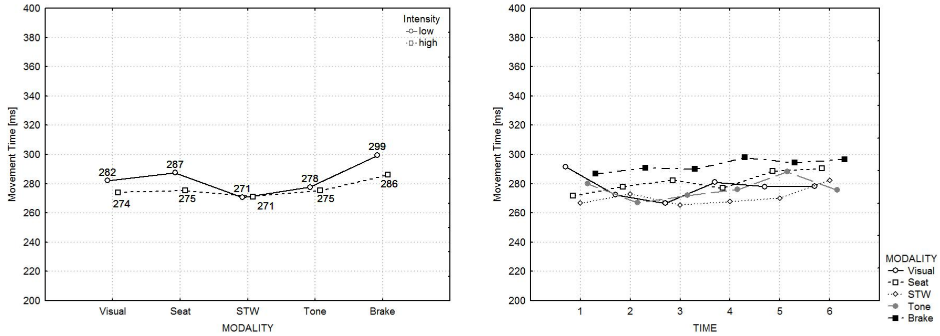
(a) Means **(b)** Boxplot

Figure 4.12: Movement Time split for Modality

post-hoc tests, are so alike that they will not be repeated here, but are part of the Appendix (cf. A.1).

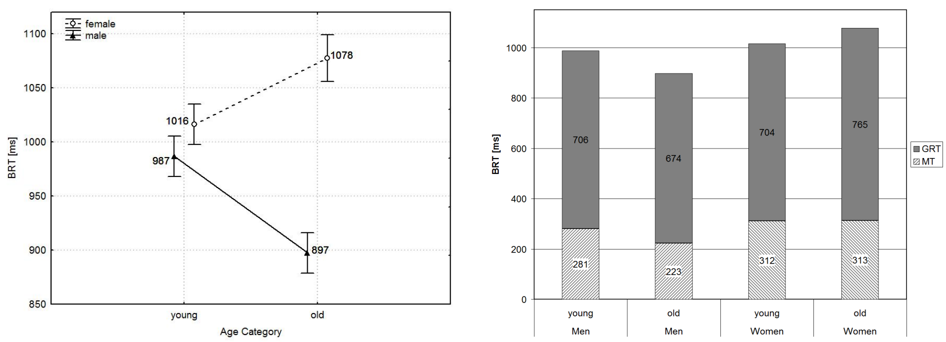
As a consequence, the movement time is very constant over all of the factors as it can be seen in, for example, Figures 4.12 and 4.13.

When checking the time components for any effect of the control variables Age and Gender, these surprisingly had one. Male participants were faster than female. Additionally, there is an interaction of Age x Gender. This is depicted in Figure 4.14a. The younger men and women on the left side differ only for about 80 ms, which is not statistically significant. But the older men (897 ms) are faster than the younger group and the older women are slower than that group (1078 ms). How does that difference build up? Figure 4.14b splits the BRT in the components Movement Time



(a) Means split for Modality and Intensity (b) Means split for Modality and Time

Figure 4.13: Movement Time

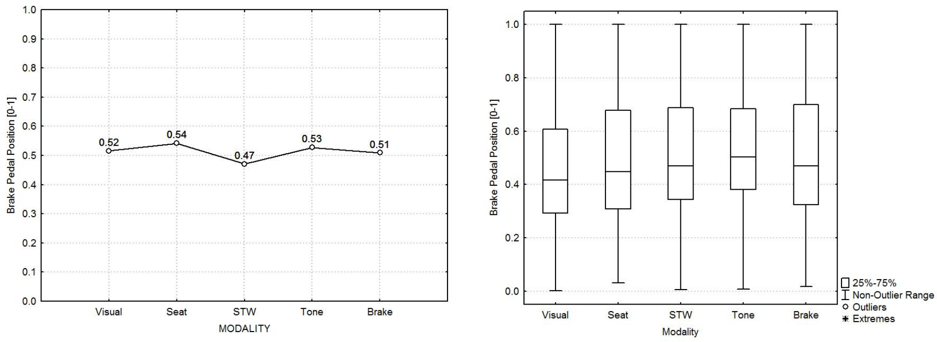


(a) Means +/- .95 percentile (b) Composition of BRT

Figure 4.14: Brake RT and the influence of Age and Gender

(MT, striped grey) and Gas Reaction Time (GRT, solid grey). Looking at the Movement Time, the men are generally faster than the women, but the older men move their foot from the gas pedal to the brake pedal even faster than the younger ones. Interestingly, the women do not differ in that time component. That means the older women lose their 66 ms on the younger women in the initial reaction time. These two components together show an advantage for the older men.

The first non-time related parameter is the first local maximum of the brake pedal position (compare also 4.2.6 on Page 82). Due to large inter individual differences, the brake pedal parameters are analyzed relative to the individual's braking maximum. This means that the first local maximum is divided by the person's absolute maximum brake pedal travel in the whole experiment. Therefore, this parameter ranges from 0 to 1.



(a) Means **(b)** Boxplot

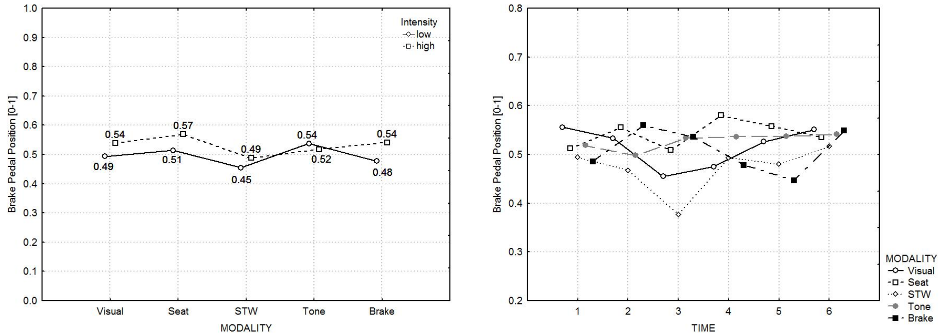
Figure 4.15: First max. brake pedal position split for Modality

Firstly, having a look at the Boxplot in Figure 4.15b shows that this parameter varies as much as possible, having almost all possible values in the upper and lower 1.5 IQR. The boxplots median lines show the highest values for the acoustic warning, whereas the mean values in Figure 4.15a show almost no differences between the Modalities except a little lower value for the steering wheel vibration. The repeated measures ANOVA results, as shown in Table 4.5, show a tendency for the factor Modality. But the factor Intensity is highly significant. The difference can be seen in Figure 4.16a. Higher intensity warnings lead to a further first depressing of the brake pedal. The mean pedal travel for the low intensity warnings is 0.495 and for the high intensity it is 0.531. The Modality × Time effect (p=0.049) is caused by the low value of the steering wheel warning in the third trial (cf. Figure 4.16b). This is a result of the post-hoc Tukey test. As this result does not seem to reflect a pattern, it is not considered further.

Table 4.5: Repeated measures ANOVA for 1st local Maximum of brake pedal position

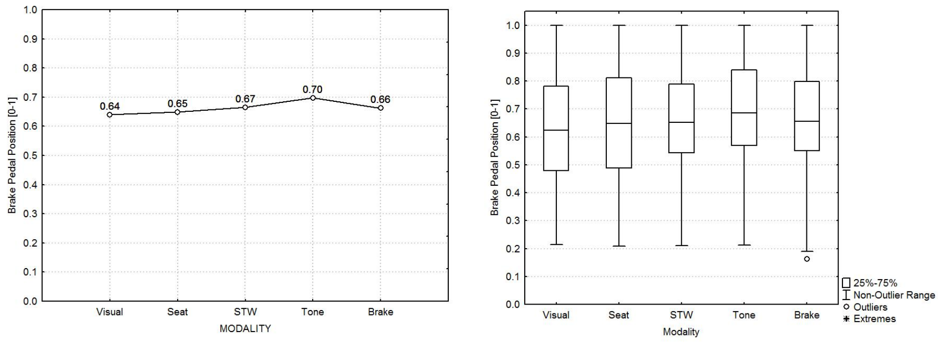
	SS	df	MS	F	p
Modality	0.50	4	0.13	2.37	0.064
Intensity	0.29	1	0.29	7.88	0.014
Time	0.26	5	0.05	0.76	0.579
Modality×Intensity	0.19	4	0.05	2.07	0.097
Modality×Time	0.83	20	0.04	1.61	0.049
Intensity×Time	0.06	5	0.01	0.42	0.835
Modality×Intensity×Time	0.34	20	0.02	0.61	0.907

The total maximum of brake pedal travel distance shows similar results



(a) Means split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.16: First max. brake pedal Position

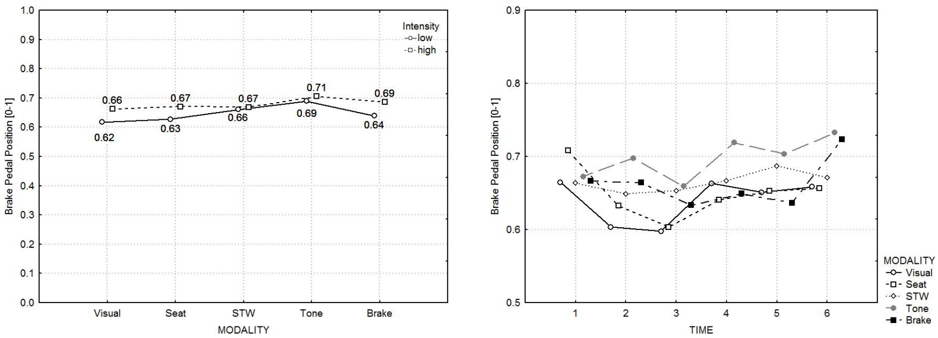


(a) Means **(b)** Boxplot

Figure 4.17: Max. Brake Pedal Position split for Modality

like the first local maximum. The mean values in Figure 4.17a as well as the Boxplots in Figure 4.17b show a slightly further travel distance for the acoustic warning. But the large variance impedes a significant main effect of the modality, and so there is a tendency with a p-value of 0.064. All the results of the repeated measures ANOVA are shown in Table 4.6. The intensity is significantly different, although again the mean values differ by only a small value of 3.6%, but the difference becomes significant. The constantly higher values can be seen in Figure 4.18a. No other factor or interaction gets close to a significant effect.

The last objective parameter is the resulting velocity at the end of the occlusion phase, which lasts 3 seconds. This parameter sums up the effect of the other preceding parameters. An early Gas Reaction Time slows

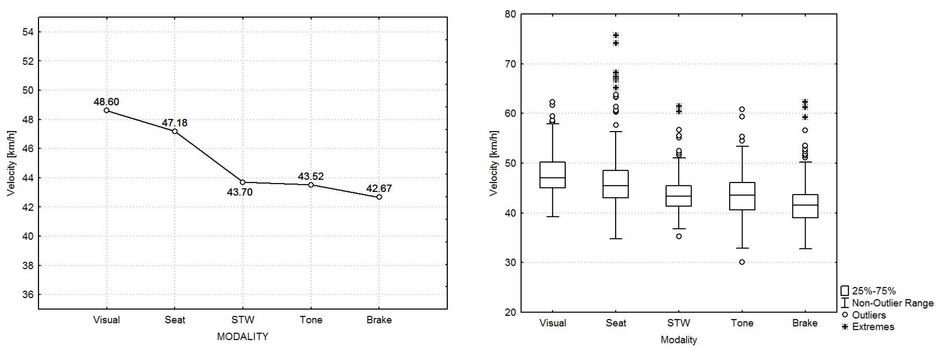


(a) Means split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.18: Max. Brake Pedal Position

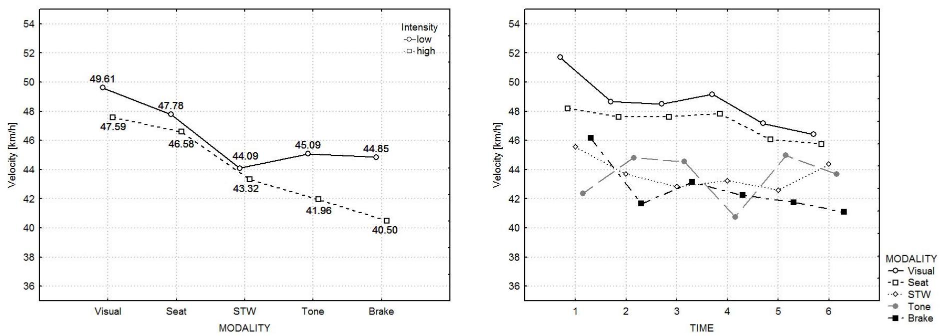
Table 4.6: Repeated measures ANOVA for Maximum of Brake Pedal Position

	SS	df	MS	F	p
Modality	0.37	4	0.09	2.35	0.064
Intensity	0.24	1	0.24	7.03	0.018
Time	0.34	5	0.07	1.09	0.374
Modality×Intensity	0.07	4	0.02	0.98	0.425
Modality×Time	0.33	20	0.02	1.54	0.068
Intensity×Time	0.04	5	0.01	0.54	0.747
Modality×Intensity×Time	0.35	20	0.02	1.46	0.096



(a) Means **(b)** Boxplot

Figure 4.19: Velocity after 3s split for Modality (data for "Brake" are adjusted by 1.3 or 8.5km/h)



(a) Means split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.20: Velocity after 3s (data for "Brake" are adjusted by 1.3 or 8.5km/h)

Table 4.7: Repeated measures ANOVA for Velocity after 3sec

	SS	df	MS	F	p
Modality	5164	4	1291	19.84	0.000
Intensity	1262	1	1262	46.35	0.000
Time	675	5	135	3.21	0.011
Modality×Intensity	409	4	102	6.79	0.000
Modality×Time	1211	20	61	2.72	0.000
Intensity×Time	247	5	49	3.86	0.004
Modality×Intensity×Time	1018	20	51	2.96	0.000

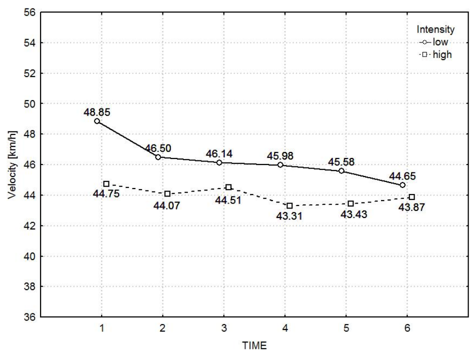


Figure 4.21: Velocity 3 sec after Warning (Intensity × Time); data for "Brake" are adjusted by 1.3 or 8.5km/h

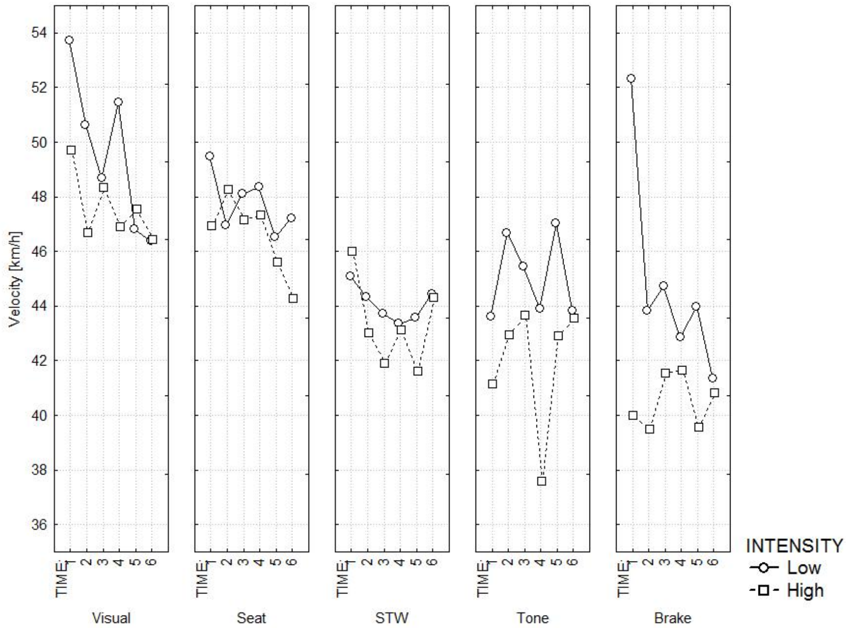


Figure 4.22: Velocity 3 sec after Warning (Modality × Intensity × Time); data for "Brake" are adjusted by 1.3 or 8.5km/h

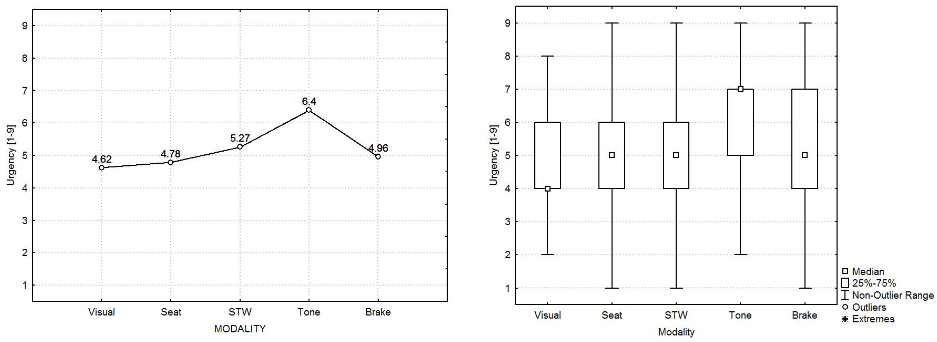
the car down during the Movement Time because of the drag torque. A short Movement Time or a fast BRT supports that even more. Whether the participant greatly depresses the brake pedal in the first movement would make a difference as well as, of course, the maximum brake pedal travel distance. As in a crash situation, the impact speed is the crucial factor for damage or injuries, and this parameter gives a good amount of information about the effectiveness of a warning. As the brake pulse decreases the velocity itself, the effect caused by the warning was subtracted from the brake pulse trials.

Figure 4.19b shows a trend for the Velocity after 3 seconds by the Modality from left to right, with the visual warning resulting in the fastest velocities and the brake pulse in the slowest. The mean value plot (Figure 4.19a) depicts the same tendency but also shows that the differences between the steering wheel (43.70 km/h), the tone (43.53 km/h) and the brake pulse (42.67 km/h) are very small. As Table 4.7 shows, every main factor and interaction is significant for this parameter. For the main factor Modality, a post-hoc Tukey test proves what has been observed by the descriptive data: The visual warning and the haptic seat lead to significantly faster velocities than the other three modalities (all p-values < 0.001). The intensity, as a main factor, effectuates a difference of 2.27 km/h, with the low intensity being at 46.28 and the high intensity at 43.99 km/h. The time also has an effect on this measure. The first trial differs from the last three. But this effect has to be further evaluated by the interactions where time is involved. Regarding Modality x Time, shown in Figure 4.20b, the biggest differences from the first to last trial are analyzed for the visual and the brake pulse warnings, which are the only combinations which become significant inside a modality. The chart for Intensity x Time (cf. Figure 4.21) shows that the difference between the first and last trial is stronger in the low intensity warnings. Taken together, this information is reflected in Figure 4.22, which shows the interaction of Modality x Time x Intensity. Each extra chart shows the interaction of Time x Intensity for a single Modality. In this chart, the differences per trial are traceable for each modality. The first trial, in the left column, for the visual warning and the right one for the brake pulse stick out because performance is greatly increased after that trial. The post-hoc Tukey test shows that these two and the fourth trial of the acoustic warning are the primary cause for the significant threefold interaction. But even without the complicated threefold interaction, one can see clear influences of modality and intensity in Figure 4.20a. Except for the steering wheel warning, the high intensity elicits lower speeds and thereby better performance inside each modality. This is also reflected in the post-hoc Tukey test. This result shows that FCW have the most effect, when they are of high intensity, regardless of the modality (except steering wheel). But the Modality has an even stronger impact on performance than intensity with the high intensity brake pulse leading to a speed of 40.50 km/h, whereas the high intensity visual warning resulted in 47.59 km/h. This is more than a 7 km/h difference. Of course there are more influencing variables that have to be taken into account before choosing a FCW. But, from a performance point of view, this is a strong argument for high intensity brake pulse or tone warnings. One part of the other influencing arguments are the acceptance and perception of the warnings by the drivers. This is the next analysis that will be discussed here.

4.3.2 Subjective Data

For the subjective data, the median in the boxplots is depicted with a square instead of a line. This was done due to the fact that many medians have the same value as the edge of a box and would therefore be not noticeable. The scales for the subjective data can be found in section 4.2.6 on page 82.

The first question after each warning trial was “How urgent was the warning?”. The judgments were medium urgent, on average (5.21). In the main factor Modality, the acoustic warning elicits the highest judgments (mean = 6.4, cf. also Figure 4.23a). In the boxplots in Figure 4.23b, the differences between the modalities is observable through the median. For the acoustic warning, the median is “7”, which reflects “very urgent”. The other medians are “5” with seat, steering wheel, and brake, and “4” for the visual warnings, which reflect the category “medium urgent”. These differences

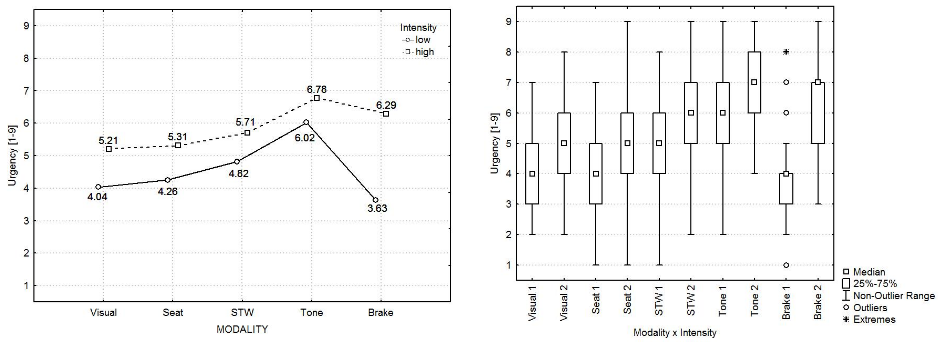


(a) Modality **(b)** Boxplot

Figure 4.23: Subjective urgency split for Modality

are also reflected in the repeated measures ANOVA. The results overview is given in Table 4.8. A Tukey post-hoc test shows that the significance stems from the acoustic warning being judged differently than the other modalities. The Intensity has an impact on the Urgency judgment. On average, the low intensity results in a rating of 4.55 and the high intensity in 5.86. In Figures 4.24 (a) and (b), it is depicted that the difference is constant throughout all Modalities. In Figure 4.23b, the low intensity is denoted with a "1" and high intensity with a "2". For all modalities except the brake pulse the difference between the intensities is one point on the judgment scale for the medians. The difference between low and high intensity is 3 scale points for the brake pulse and thus ranging from the lowest to the highest medians of the other modalities. The interaction of Modality $\times$ Intensity is highly significant, too. But as in the post-hoc test, almost all combinations are significant, so this does not add clarification.
As there was a significant effect for the BRT regarding age and gender of the participants, this was also checked for the subjective Urgency. Figure 4.25 depicts the mean values of these influences. For descriptive reasons, a factorial ANOVA was calculated with the two categorical factors Age and Gender. This revealed tendencies $p<0.1$ for both main factors as well as interaction but no significant influences. Due to this, and the fact that impact is much smaller than that of modality and intensity, this is not followed further.

The answers to the question "How serious was this warning?" are very similar to the answers presented for the Urgency. The correlation of the two judgments makes sense: A serious warning should convey a certain urgency. Hence, the means and the boxplot in Figure 4.26 (a) and (b) look very similar as those for the Urgency (Figure 4.23). Again, the tonal warning gains the



(a) Means (b) Boxplots

Figure 4.24: Subjective urgency split for Modality and Intensity

Table 4.8: Repeated measures ANOVA for subjective Urgency

	SS	df	MS	F	p
Modality	361.87	4	90.47	15.08	0.000
Intensity	384.42	1	384.42	139.04	0.000
Time	2.77	5	0.55	0.52	0.759
Modality×Intensity	107.85	4	26.96	21.18	0.000
Modality×Time	23.7	20	1.18	1.47	0.090
Intensity×Time	0.53	5	0.11	0.15	0.978
Modality×Intensity×Time	16.97	20	0.85	1.44	0.105

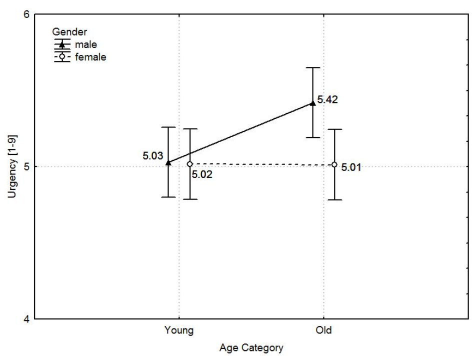
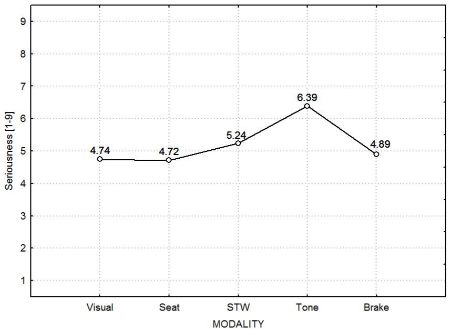
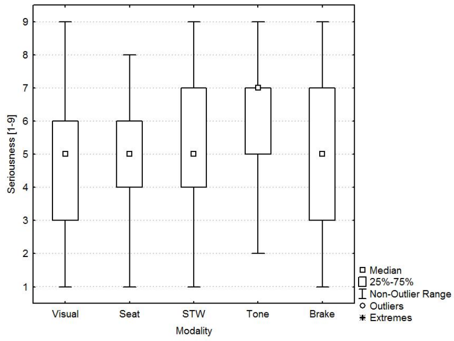


Figure 4.25: Dependency of subjective urgency assessment by Age and Gender

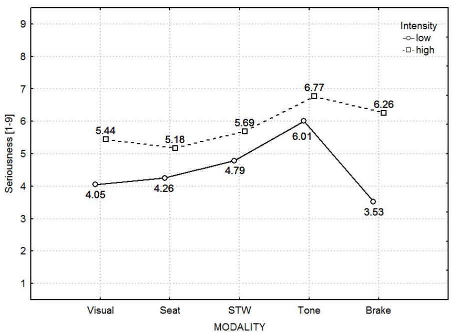


(a) Modality

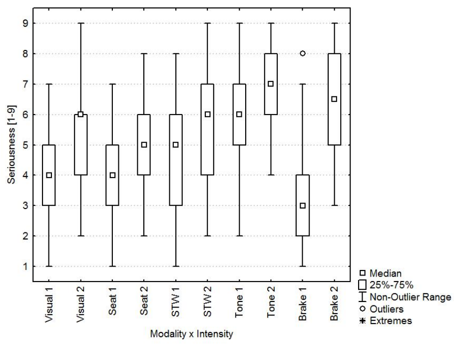


(b) Boxplot

Figure 4.26: Seriousness split for Modality



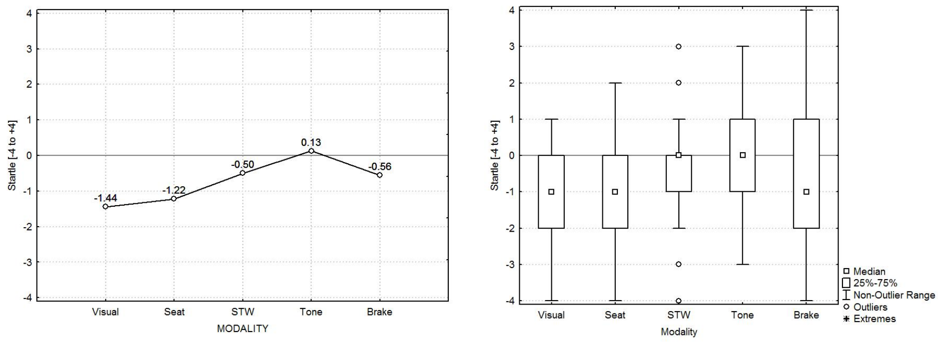
(a) Split for Modality and Intensity



(b) Means split for Modality and Time

Figure 4.27: Seriousness Modality × Intensity

highest results with a mean of 6.39 and differs significantly from the other modalities with a p-value < 0.001. The main factor Intensity is significant (p <0.001) as well as the interaction of Modality × Intensity ($p < 0.001$). The means and boxplots of this interaction are depicted in Figures 4.27. The high intensity warnings lead to higher judgments about the seriousness of the warnings. The post-hoc test for the interaction shows that this effect is mainly caused by the high ratings of the low intensity acoustic warning and the large difference between ratings for the brake pulse warnings between low and high intensity. Furthermore, this time the threefold interaction Modality × Time × Intensity is significant ($p=0.04$). The post-hoc test shows that this is caused by the fact that the ratings high intensity visual and brake pulse warnings decrease over time, while the others remain constant.

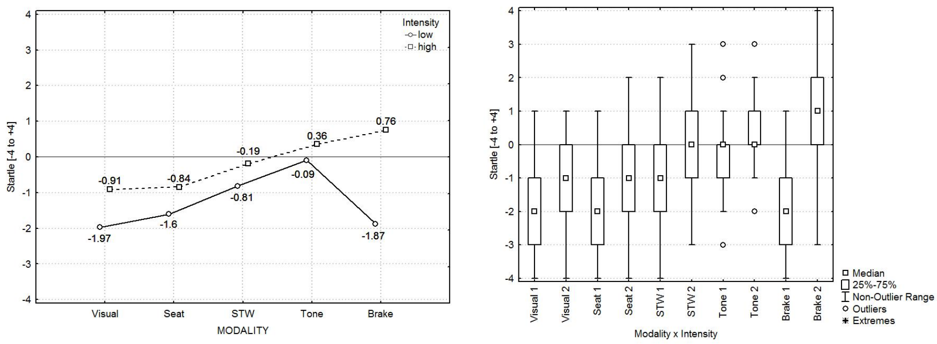


(a) Means **(b)** Boxplot

Figure 4.28: Startle split for Modality

The scale for the question "How much did the warning startle you?" was the only scale that had an optimum in the middle. When the participants thought the warnings startled them at an adequate level for a collision warning they were instructed to judge this as a zero. Regarding the mean values for Modalities in Figure 4.28a, the best results are achieved with the acoustic warning (mean=0.13), followed by the steering wheel (mean= -0.50) and brake pulse (mean= -0.56). The boxplots in Figure 4.28b show that the distribution of the acoustic warnings is balanced at around zero, but the steering wheel vibration has the least spread of distribution of answers close to zero. The repeated measures ANOVA gives a significant result for the factor Modality (cf. Table 4.9). The post-hoc Tukey test reveals that steering wheel, tone, and brake pulse differ from visual and seat, but steering wheel and brake pulse do not differ among one another. The tone differs also from the brake pulse. The effect of the intensity shows that higher intensity leads to more a perceived startle effect. The interaction of Modality × Intensity is also significant on a p-level < 0.001 (cf. Table 4.9). Both plots in Figure 4.29 show a clear effect of the intensity on the perceived startle effect per Modality, except for the acoustic warning, where the post-hoc test only results with a tendency within the modality. In the boxplots in Figure 4.29b, "Tone 1 & 2" are the only distributions with a spread of the central 50% fall between one scale step. For the other distributions it is always 2 scale steps. With the median for both intensities being at zero, the acoustic warning is closest to the optimum. The worst results give the low intensity visual warning and brake pulse. Both warnings are clearly judged as startling the driver too little for being an effective collision warning.

Another important judgment is the rating of how annoying a warning is. This question as well as the one for Appropriateness were asked in only the first half of the experiment. The plots in Figures 4.30 (a) and (b) show



(a) Split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.29: Startle Modality x Intensity

Table 4.9: Repeated measures ANOVA for subjective Startle

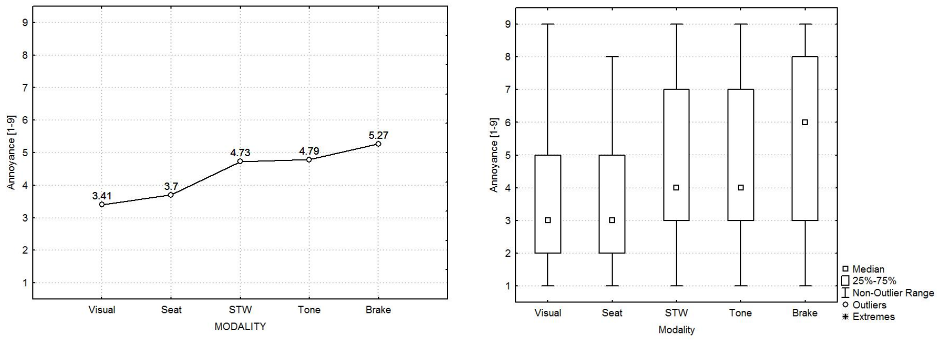
	SS	df	MS	F	p
Modality	361.87	4	90.47	15.08	0.000
Intensity	384.42	1	384.42	139.04	0.000
Time	2.77	5	0.55	0.52	0.759
Modality×Intensity	107.85	4	26.96	21.18	0.000
Modality×Time	23.70	20	1.18	1.47	0.090
Intensity×Time	0.53	5	0.11	0.15	0.978
Modality×Intensity×Time	16.97	20	0.85	1.44	0.105

the highest annoyance assessments for the brake pulse warning (mean=5.27) and the lowest for the visual modality (mean=3.41). Furthermore, the boxplot for the haptic seat in Figure 4.30b is the only warning type that has no ratings at "9" (most annoying). It seems that this warning, along with the visual warning, is the least annoying. The results of the repeated measures ANOVA, as written down in Table 4.10, show a significant effect of the factor Modality ($p<0.001$). The Tukey post-hoc test shows that the visual warning is lower than the steering wheel, tone, and brake pulse, and that the seat differs from the brake pulse. This confirms the statements based on the descriptives: The brake pulse is the most annoying, while the visual and seat warnings are the least annoying modalities. The factor intensity has an impact of 1 scale step, which is significant with a p-level < 0.001. Time also has an impact, but it changes from only 4.11 in the first trial to 4.56 in the last. Although the effect is significant, the impact seems to be very low as this is less than half a scale point. The interaction of Modality $\times$ Intensity is very interesting as the differences for the intensities inside a modality are not significant in a post-hoc test except for the brake pulse warning. Furthermore, the high intensity steering wheel, tone, and brake pulse warnings are more annoying than any visual or seat warning. The high intensity brake pulse warning is even more annoying than any other warning in this experiment. The threefold interaction of Modality $\times$ Intensity $\times$ Time is based basically on the fact that the ratings of the high intensity visual warning and the low intensity brake pulse increased by 1.2 scale points, and the low intensity tonal warning increased by 1.45 scale points from the first to the second trial. The other Modality/Intensity combinations were more constant over time. So, the low warnings of tone and brake pulse were perceived as more annoying the more often they were experienced. But this does not change the statement that the low brake pulse differs from the strong brake pulse. In the post-hoc test this is true for the early and the late judgments. As

Table 4.10: Repeated measures ANOVA for subjective Annoyance

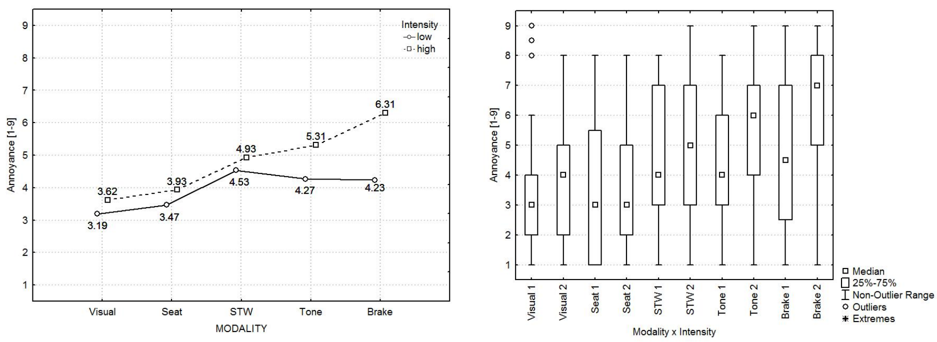
	SS	df	MS	F	p
Modality	225.00	4	56.25	6.99	0.000
Intensity	88.00	1	88.00	34.43	0.000
Time	17.37	2	8.69	4.50	0.020
Modality×Intensity	46.40	4	11.60	5.77	0.001
Modality×Time	12.43	8	1.55	1.59	0.135
Intensity×Time	1.36	2	0.68	0.80	0.458
Modality×Intensity×Time	28.08	8	3.51	3.15	0.003

for the objective data, the last subjective parameter is an integrative one: "How appropriate it this signal as a FCW?". The means plot in Figure 4.32a shows a very similar curve to that seen with Urgency and Seriousness. The



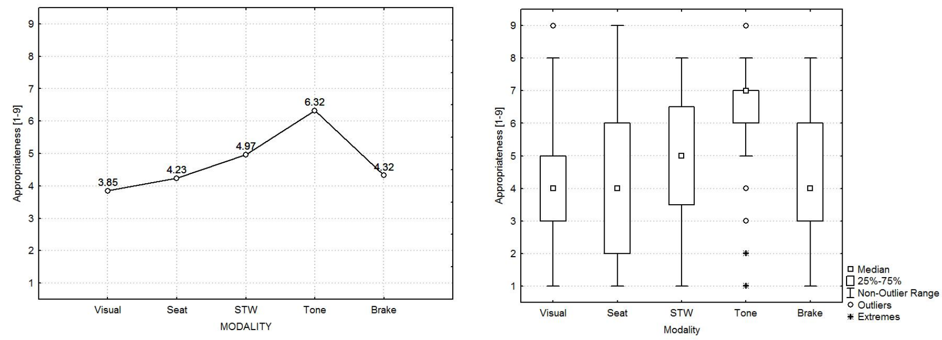
(a) Modality **(b)** Boxplot

Figure 4.30: Annoyance split for Modality



(a) Split for Modality and Intensity **(b)** Means split for Modality and Time

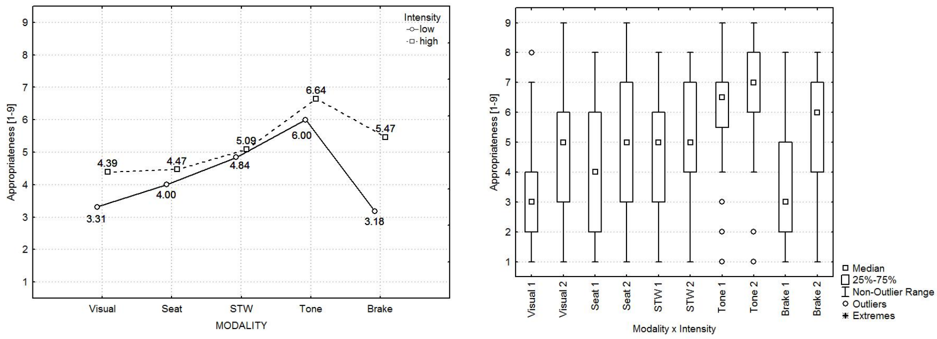
Figure 4.31: Annoyance Modality x Intensity



(a) Modality **(b)** Boxplot

Figure 4.32: Appropriateness split for Modality

rating for the acoustic warning sticks out with a higher value than the other modalities. This is even more salient in the boxplot Figure 4.32b, because the spread is small and the median sits at "7", which refers to the verbal category "very much". The results of the ANOVA can be found in Table 4.11. There it says that the modality has a significant effect on the ratings of Appropriateness. The Tukey post-hoc test shows that the acoustic warning is rated better than any other Modality. There are no other significant differences. The factor Intensity is also significant ($p<0.001$). Higher intensities lead to better assessment of the signals. Time has no influence on the ratings. The interaction Modality $\times$ Intensity, again, is highly significant ($p<0.001$). From a descriptive standpoint, the ratings of the two steering wheel intensities do not differ, while the others do. But the post-hoc test shows that only the visual warning and the brake pulse differ between their low and high intensity variants in the judgment. The high intensity acoustic warning is rated better than any other presented warning except for its own low version. Regarding this rating, the worst warning types, are the low intensity visual warning and the low intensity brake pulse. They are rated worse than all the other warnings except for the low intensity haptic seat. It is interesting if the subjective and objective measures are linked. The most interesting subjective variables for that question are the perceived urgency and the assessment of appropriateness as a FCW. To see if these judgments are connected to an objective measurement, correlations were calculated with the objective measures used in the analysis (see Section 4.3.1). The only relevant result was the correlation between the BRT and the conveyed Urgency. The correlation is significant on a p-level of 5% with $r = -.41$. The relationship is also depicted in the scatterplot in Figure 4.34. The faster the participants reacted, the higher they rated the Urgency. This is an encouraging result because this shows that the conveyed Urgency has a



(a) Split for Modality and Intensity **(b)** Means split for Modality and Time

Figure 4.33: Appropriateness Modality x Intensity

Table 4.11: Repeated measures ANOVA for subjective Appropriateness

	SS	df	MS	F	p
Modality	340.03	4	85.01	8.53	0.000
Intensity	100.35	1	100.35	25.62	0.000
Time	0.29	2	0.14	0.09	0.914
Modality×Intensity	59.26	4	14.81	8.01	0.000
Modality×Time	4.74	8	0.59	0.55	0.816
Intensity×Time	2.81	2	1.40	1.10	0.346
Modality×Intensity×Time	1.20	8	0.15	0.19	0.991

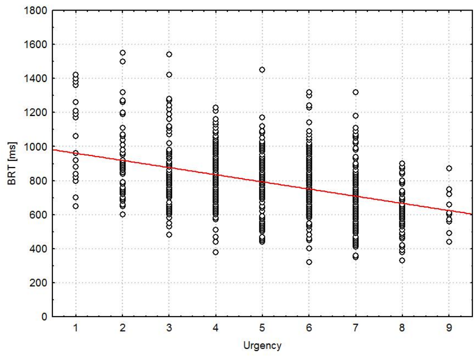


Figure 4.34: Scatterplot of BRT against Urgency

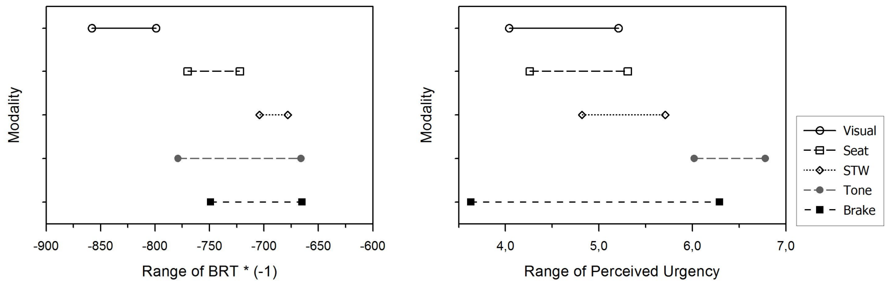
direct effect on the reaction time.

4.3.3 Summary of Results

Modality and Intensity have an effect on objective and subjective measures. Regarding the objective measures, Modality and Intensity have a stronger impact on the reaction time based measures than on the reaction intensity based ones. The effect sizes of these factors on BRT and GRT are bigger than on Brake Pedal Maximum or first local Brake Pedal Maximum. Stimuli with higher intensities lead to faster reaction times. In regards to BRT, the warning types steering wheel vibration, tone, and brake pulse lead to the best results. This is followed by the haptic seat, while the visual warning elicits the slowest reactions. These results were averaged over all trials. The participants seem to learn to observe the visual display and their reactions improve over time. For the other modalities the results are more stable. Therefore, the differences between the modalities are the largest at the first warning.
For BRT, the difference between the best (high intensity brake pulse) and the slowest (low intensity visual) mean is 193 ms. At a speed of 80 km/h this time equals a distance of 4.3 m or the length of a car.
Unexpectedly, there was an Age × Gender effect for the reaction times. Younger male and female participants had almost the same BRT but the group of older women was slower and the group of older men was faster. The older men had a faster GRT and a faster movement time.
For the resulting parameter velocity at the end of occlusion, the result for the factors Intensity and Modality are similar to the results for the brake reaction time. Steering wheel, tone, and brake pulse lead to the best results, which are the slowest velocities. In trials with a vibrating seat or visual warning, the speed is higher at that point in time. The best consistent results are achieved with the high intensity brake pulse, while the high intensity tonal warning proves to be second best.

For the subjective ratings the results point in a clear direction: The acoustic warning is the most urgent and serious one, has the right startle intensity, has medium annoyance potential and is rated most appropriate as a FCW. For the question of appropriateness, the small spread of the acoustic warning is a big advantage. Of the 96 times this question was asked, only five times was the answer rated in the category “little appropriate”. All the other times it was rated as “medium” or “very appropriate”. The high intensity visual and haptic seat variants have potential for a part of the collective of participants. The answers used the whole scale and where individually different. The low brake pulse and the low visual warnings are constantly rated badly (not urgent enough, do not startle) and the low brake pulse is still rated as being quite annoying (4.23).
One of the research questions (cf. page 74) was if there is something like an “operating range” for the warning actuator. Of course the results are highly dependent on the experimenter’s choice of warnings, but the actuators and intensities chosen were as close to production solutions and scientific recommendations as possible. Within these constraints, the differences between low and high intensity results reflect an operating range for possible in-car solutions. Most relevant for warning design are the perceived Urgency and the (Brake) Reaction Times on the signal. To illustrate this, in Figures 4.35 (a) and (b) the mean values of BRT and perceived Urgency are plotted in a different way. Note that the BRT is shown with a negative prefix to achieve that urgency and BRT shows good results (high urgency / fast RT) on the right. For the BRT, this view shows that tone and brake pulse have a wide range and, therefore, entail the risk of doing something wrong while the modality has the possibility to elicit a fast warning. This plot also shows, again, that in regards to BRT, steering wheel vibration, tone, and brake pulse do not differ in the high intensity. Also, the haptic seat is within the range of tone and brake Pulse. It is only the visual warning that is far behind in the ability to trigger fast responses. For the possibility of communicating urgency, the brake pulse has the widest range. The tone variants used here generally do well in communicating high urgency. Visual warning, haptic seat, and steering wheel vibration have ranges in the middle of what is perceived to be in the brake pulse range.

Altogether, the steering wheel, tone and brake pulse elicit comparably fast (good) reactions but the tone is rated better from a subjective standpoint. The visual warning, especially the low intensity version, causes the slowest and weakest reactions and is assessed as inappropriate. The haptic seat occupies a position in the middle.



(a) BRT * (-1) **(b)** Urgency

Figure 4.35: Range of Modalities

4.4 Discussion

The differences of intensity are a replication of what Piéron (1913) demonstrated and what is since known as the Piéron Law: Higher intensity stimuli result in shorter simple reaction times. As explained in section 2.1.6, one cause for this effect is thought to be the higher arousal of higher intensity warnings. As this study was done for the applied field of driver warnings, several Industry Standards and suggestions from research were followed. Therefore, the loudness of the acoustic warning was set to one value for both intensity levels. To achieve different intensities, the frequency was changed. Hence, the physical intensity (amplitude) of the 2000 Hz tone was not higher but even lower than the 250 Hz tone. Although not a goal of this experiment, the result that the 2000Hz sound leads to faster reactions adds to the arousal discussion. It seems that (physiological) arousal elicited by a higher physical intensity cannot be the only explanation. So this result shows the explanation cannot solely be based on physiological cause, but there is a clear psychological effect.

How can the differences between the modalities be explained? In the present experiment the modalities showed different operating ranges, but also resulted in overlapping BRT. When do different modalities elicit the same reaction times? Kohfeld (1971) showed that reaction times can be equal for visual and acoustic signals if the perceived intensities are the same. This was achieved in his work by a prior cross-modality-matching. He also showed that there is a limitation; that this dependency works only in-between certain boundaries. Below approximately 50 dB, sounds elicit faster responses, although the subjective intensities were matched (see Figure 4.36). Hence, the BRT results from the following factors: the subjective intensity, physical intensity, and the modality of the stimulus. So, there are differences between the modalities that can not be compensated for and are specific to each stimulus type. In the present experiment, intensities were not asked or

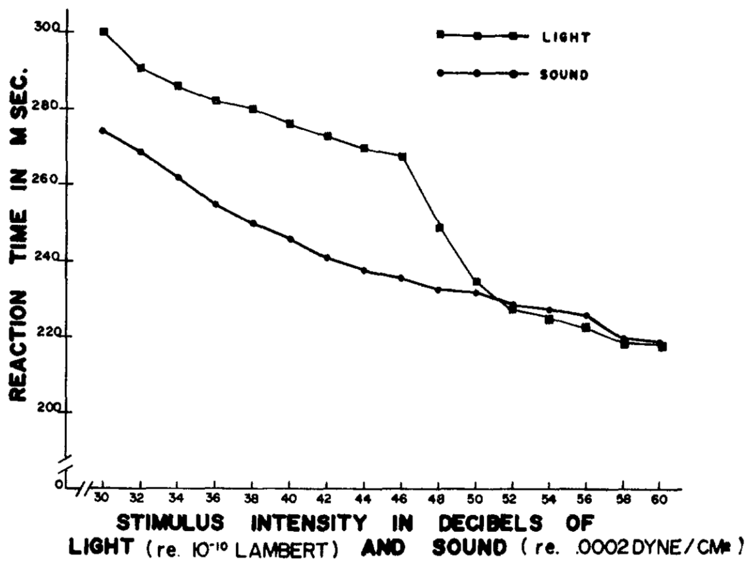


Figure 4.36: Mean RT as a function of stimulus intensity of light and sound (taken from Kohfeld (1971) p.256)

matched but the significant correlation between BRT and perceived urgency shows that a comparable dependency exists.
The results in Figure 4.35 show that there are substantial differences between the warnings used in regard to subjective urgency and reaction time. As this study closely followed industry standards and research suggestions, it provides an overview on driver reactions in a laboratory setting to warning variants in their current boundaries of implementation.

As for the question of the support for anticipation, perceived urgency as well as possible reaction times play an important role. As a FCW is a rare event, the perceived urgency should be an important factor when communicating the need to react. This should be true especially for the first warning, when the meaning is not known to the driver.

Chapter 5

Study Two: Urban traffic scenario

Study One offers insight into detailed aspects of braking reactions to a set of typical warning types. The different warnings, for example, lead to brake reaction time differences of up to 200ms. As already pointed out, at a speed of 80 km/h, this time equals the length of a car. But drivers have maneuvered through traffic quite well for a century without active safety assistance systems. The main question of this experiment is under which boundary conditions does a Forward Collision Warning help and does the type of warning play a role? Here, boundary conditions are understood to be physical conditions of the traffic and psychological conditions and, in this particular, case anticipation levels of the driver. The role of anticipation was the subject matter of Section 2.1.2.

The main interest in this experiment is the interaction of the presence, particularly the absence of Forward Collision Warnings, and different levels of threat anticipation in different driving scenarios. The study was also designed to identify if the influences of the different warning types found in the laboratory setting are still valid in more realistic and complex situations. To comfirm the results found in the first experiment, a replication of this was performed at the end of this study.

5.1 Research Questions

The questions that are addressed by this study are

- Does an additional stimulus, as a warning, facilitate crash avoidance behavior in an attentive driver?
- Is the quality of the warning still relevant when the driver can see a *real* threat?

- Does the emergence of a situation influence the anticipation of the driver?
- Might a wrong anticipation be a cause of missing crash avoidance behavior?
- Is it possible that a warning substitutes the driver's threat anticipation?
- Does the effectiveness of a warning differ if a hazardous object has been part of the scene for a longer time or if it appears suddenly?
- Does the familiarization with a FCW system lead to delayed reactions even when anticipation of the real threat might be possible?
- Is the way the threat appears of relevance for the effectiveness of the warning?
- What influence does the design of the warning itself have on the complex interactions brought up before?

5.2 Methodology

A complex urban scenario was installed into a driving simulator with the goal to answer all of the research questions. In this study's simulated scenario, , only one-way streets were used for the participants' route. This was invented to offer the possibility to implement threats from the right as well as from the left with equal distance to the participant. Therefore, participants could not expect only suddenly appearing threats always from one side. On a "normal" street with oncoming traffic, the distance to the right street edge is nearer and could have encouraged the participants to monitor this side.
The scenarios always followed an alternating pattern between narrow streets with a 30 km/h speed limit and wider streets with a 50 km/h speed limit. The narrow streets were winding. Because of that, the participants were forced to slow down. These speed changes and curves were implemented to make sure that the participants were used to the foot movement between gas pedal and brake pedal. This was necessary because, in this case, a computer gaming pedal system was used. Consequently, they would hit the brakes reliably in the target situations.
Following the discussion on attention/inattention (see sec2.1.4 on page 14), the participants in this study should be attentive drivers, according to Klauer et al. (2006). To ensure that the participants looked in the forward direction, a one screen simulator solution was chosen. Additionally, an on screen speedometer was implemented. All information was displayed on a 21 inch screen. Hence, the driver had the ability to see all information – at least peripherally. This is crucial for the argumentation.

Figure 5.1: Driving Simulator

Figure 5.2: Original Screenshot

5.2.1 Simulator

This study was conducted in a simple non-moving driving simulator (see Figure 5.1). The simulator consisted of one commercially available PC, a BenQ 21 inch wide screen monitor, a Logitech MOMO Force Feedback Racing Wheel with gas and brake pedal, Philips SHL9500 headphones, and an Elta MA100 massage mat on an office chair. As in the first study, SILAB simulation software was used. The simulator had no additional displays. The speedometer and the visual warning were displayed "on screen". As one can compare in Figure 5.2, the speedometer was displayed in green digits in the lower right corner of the screen. The black bar in the low center of the screen was used to display the visual warning.

Driving Scenarios

As pointed out at the beginning of this section, the simulated scenarios were situated in an urban area. The participants' route consisted of one-way streets only. Navigation was easy because the participants only had to follow the course of the street. Streets that cross or merge the participants' route were mainly streets with oncoming traffic as well as some one-way streets. As stated earlier, there was a constant change between 30 and 50 km/h areas. The 50km/h sections had a length from 400 to 1000m and the 30 km/h sections varied between 200 and 500 m in length. One combination of a 30 km/h and a 50 km/h section will be called a module. Altogether, the participants had to drive through 30 modules. Twenty of the modules were harmless and ten modules included potentially hazardous situations. In all modules light traffic was simulated and pedestrians often walked on the sidewalks or crossed the streets at traffic lights or at crosswalks. This was simulated to give the driver the impression of a lively urban area. Therefore, the majority of road users were innocuous. In the experiment, there were nine different types of target scenarios. This resulted from a 3 $\times$ 3 plan (cf. 5.1). There were three different threat types and three levels of threat anticipation. The three threat types were

1. the lead vehicle brakes,
2. a pedestrian crosses the street, and
3. a car from a side street takes the right of way.

The three levels of anticipation were accomplished with different behavior from the other road users or with different surroundings. The road user that shows the behavior that provokes a potential crash scenario will be called “hazardous road user” (HRU) from now on. The HRU could be another vehicle or a pedestrian. When anticipation was possible, the HRU showed

Table 5.1: Driving scenarios

	Anticipation		
Type of threat	possible	not possible	wrong
Braking			
Pedestrian crossing			
Taken right of way			

behavior some seconds before the risky behavior that showed that he will become a threat. If anticipation was not possible, this antecedent behavior was not shown or not observable. In the scenarios in which the anticipation level was wrong, the driver’s anticipation was misguided by introducing a second, but incorrect, threat. It is essential to notice that the dangerous behavior of the HRU itself was the same for every type of threat. The scenarios will be described in detail in the following.

Preceding Car Brakes In this scene, the Hazardous Road User was always a hard braking car in front of the EGO vehicle. The preceding car was introduced in the scene either because it drove out of a parking space or was waiting at a red traffic light. Then the car accelerated to a speed of 50 km/h. After holding that speed for a few seconds, the car was programmed to drive at a distance of 30 m in front of the participant. At a fixed point on the street, the HRU braked hard with a deceleration of $9.8 m/s^2$. This resembled full braking on a dry road. In all of the three variants of the scenario, a warning was issued 500 ms after the start of braking.
The difference between the three anticipation levels lies in the behavior of the HRU before the dangerous braking event. The Figures 5.3 to 5.5 depict the scenes in a schematic way. In the anticipation level *possible*, the HRU used the turn signal to the left for 3 s and then for 2 s to the right at a section where there was no merging street nearby. Then the HRU started to decelerate. The goal was to create the impression that the driver of the preceding

Possible **Not Possible** **Wrong**

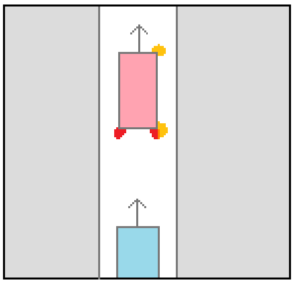


Figure 5.3: Brake, AP possible

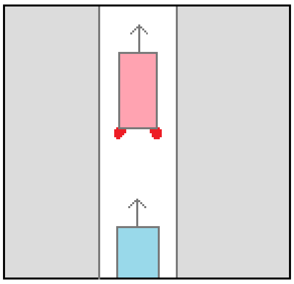


Figure 5.4: Brake, AP not possible

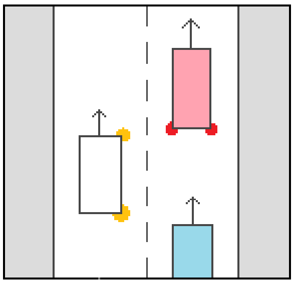


Figure 5.5: Brake, AP wrong

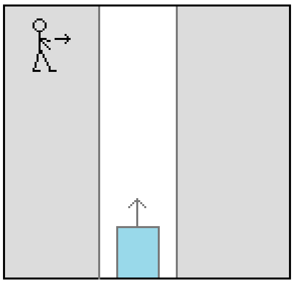


Figure 5.6: Pedestrian X-ing, AP possible

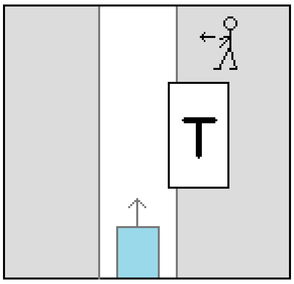


Figure 5.7: Pedestrian X-ing, AP not possible

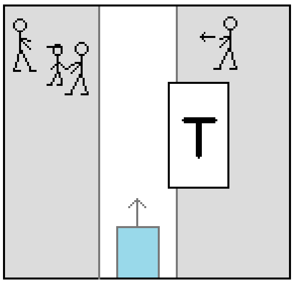


Figure 5.8: Pedestrian X-ing, AP wrong

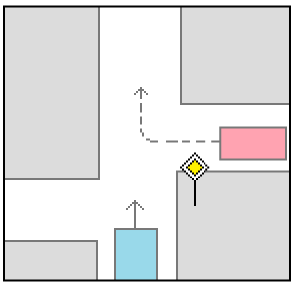


Figure 5.9: Right Of Way, AP possible

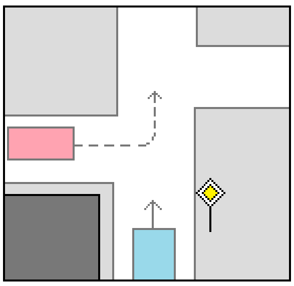


Figure 5.10: Right Of Way, AP not possible

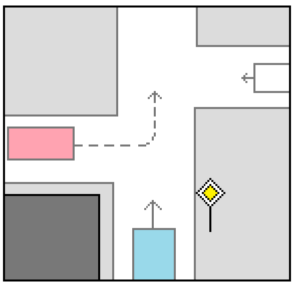


Figure 5.11: Right Of Way, AP wrong

car was looking for a parking space and hence the participant could assume the car would come to a stop. After stopping the car, the HRU parked in a parking space on the right. In the anticipation *not possible* scenario, the HRU stopped at a comparable section of the street. But there was no usage of the turn signal ahead. Therefore, the braking should have been totally unexpected. After the stop, the car proceeded down the street. For the anticipation level *wrong*, the HRU showed exactly the same behavior as in *not possible*. But this time the street was a two-lane one-way street. The participant followed the HRU in the right lane at a 30 m distance. Then a third car passed the participant on the left lane and used the turn signal to the right. Two seconds later, the HRU (lead car) started the braking maneuver. After a three second stand still, the HRU parked. The third car created the impression that it wanted to cut into the gap in front of the participant. Hence, the assumption was that the participant would monitor this car as it showed the behavior which would most likely lead to a hazard. But against expectations, the lead vehicle braked.

Pedestrian crosses the street The HRU (i.e., the source of danger) in these scenarios was always a pedestrian who crossed the street. The different levels of possible anticipation were constructed by using line-of-sight obstruction. The scenes are schematically shown in Figures 5.6, 5.7, and 5.8. In the scene where anticipation is possible, the pedestrian who walked from the sidewalk onto the road was clearly visible from a distance of about 90 m. If the participant proceeded to drive at 50 km/h, the EGO car would have hit the HRU. In the other two scenes (*not possible/wrong*), the last few meters of the pedestrian's path were exactly the same except that the starting point and movements were mirrored to the right side of the street. A transporter obstructed the participant's view of the HRU. The transporter is marked with a "T" in Figures 5.7 and 5.8. Therefore, the participant saw the pedestrian at a distance of 50 m the first time. Additionally, in the scene with the anticipation level *wrong*, three pedestrians on the left sidewalk walked close to the road curb. One of these three was a child. It was assumed that the driver would observe the three pedestrians because there was the possibility they might walk onto the street. But then the hidden HRU crossed the street from the right.

Another Car Takes The Right Of Way In these three scenarios, the source of danger was a car that took the right of way from the participant. The movement of the dangerous car was programmed in such a way that it was influenced by the speed of the EGO car and hence would provoke an accident unless the participant slowed down. This scenario did not force the driver to perform a full stop, but he had to brake. The Figures 5.9, 5.10, and 5.11 depict the scenario schematic. As in the Braking scenario, the blue box

Figure 5.12: Elta MA100 massage mat

Figure 5.13: Elta MA100 in simulator setup and position of tractors

represents the EGO car and the red box substitutes the dangerous car. In the scene where anticipation is possible, the participant had an unobstructed line of sight to the car in the side street (see Figure 5.9). The other car (red in Figure) is obviously not slowing down although, according to the traffic signs, it should stop for the EGO car. This should give the impression that the driver of the other car might / will take the right of way from the participant. Therefore, the participant can anticipate this threat. In the pictures for the anticipation levels *not possible* and *wrong* is a dark box in the lower left corner. This symbolizes a house. Because of this house, which is located very close to the curb (1 m distance), the participant was able to see the dangerous car only in the last second. This was the major difference in the scene with anticipation *possible*. The participant had the right of way and could not see another road user in the scene *not possible* anticipation. Therefore, the threat emerged very suddenly. The third scenario was exactly equivalent to the scene without anticipation, except that another car is introduced. In Figure 5.11, it is depicted with a white box. This car is clearly visible to the participant for about 3 s before the dangerous car appears. The other car approached the junction. When it was visible for the first time it was moving at a fast pace, but immediately started to slow down. It is assumed that the participants kept track of this car because it was the only potential threat before the dangerous car appeared.

5.2.2 Warnings

The warnings used in this experiment were derived from the first experiment. Three warnings were used this time: a visual, an acoustic, and a haptic seat warning were implemented. The visual and the acoustic warnings correspond to the high intensity ones from Study One (for a detailed description of the visual and the acoustic warning, compare Section 4.2.2). For the visual warning, the only difference was the location. In Study One, it had been displayed on a separate display. In this study, it was integrated into the screen that was used. In Figure 5.2 on page 109, one can see a black bar in the lower center. This bar was displayed throughout the whole experiment regardless of the warning condition the participant was in. For the participants with the visual warning, this was the place where the warning was displayed. As in the first experiment, the acoustic warnings were played via the headphones. The values from Table 4.1 on page 79 for the 2000 Hz warnings were applied. As the simulator mock-up was different from Study One, the in-seat vibration had to be displayed via another tool. An Elta MA100 massage mat (cf. Figure 5.12 was used on an office chair. It was linked to the simulator via an electronic USB Switch which has a latency of 2 ms. Similar as the warning in Study One, only the two front tractors underneath the participants' thighs were activated. The exact position is marked with red ovals in Figure 5.13. The tractors generated a similar intensity as the high intensity warning in the simulator in Study One, but the motors needed a longer time to stop as the ones used in Study One. Therefore, a 100 ms on/off period was not possible. To match the 900 ms duration of all warnings, a 180 ms on / off period was introduced for this study. This timing effectuated three distinct motor activations for the participant at a similar intensity to Study One.

5.2.3 Participant Sample

79 persons participated in this study. These people were highly trained in simulator driving. This means that they had at least a 3 hour training session (cf. S. Hoffmann & Buld, 2006) and had usually participated in other simulator studies in the WIVW facilities. Half of the participants were female, half were male. The age ranged from 22 to 66 years. The participants were split into two age groups. In the young group, the age ranged from 22 to 33 years, whereas the older group's age ranged from 51 to70 (see also Table 4.3). All drivers in this study have held a German driver's license for at least 4.5 years. Their driving experience during the past 12 months varied between 500 and 65000 km.

Table 5.2: Information on participant sample

Group	Age mean [yrs]	Age SD	License mean [yrs]	12 month experience [km]	N
Female	33.79	9.46	16.96	11183	35
Male	34.54	11.88	14.74	15022	44
Total	34.12	10.13	15.83	13403	79

5.2.4 Experimental Procedure

In the beginning of each experiment the participants gave their consent for collecting demographic data, questionnaire data, and simulator data and to publish their data, when it is anonymized (see Appendix B, page 174). The participants were told that the main interest of the study was natural driving behavior in urban driving situations. Although all drivers were trained simulator drivers, the simulator set-up was different to what participants were used to. Therefore, an additional 15 minutes of training was introduced. The main focus of the first 10 minutes was to train targeted braking maneuvers at stop sign stop lines. The aim of the training was for participants to become accustomed to the gaming pedal system. The training was separated into 2 minute sections. After each section the experimenter asked if the participant was confident with the task. If the participant did not state that he was confident, the section was repeated. After the training, all participants were able to perform targeted braking with initial velocities of 30 km/h and 50 km/h. In the last five minutes of the training session the simulated scenario was the same as in the main experiment. Although all participants were well trained in simulator driving, they were told that this section was intended for participants who had not been driving in the simulator before and, therefore, didn't know the urban scenario and that the experimenter wanted everybody at the same level of knowledge about the scenery possibilities. The participants were instructed that the traffic regulations had to be observed and that they should drive as naturally as possible. The only limitation was the speed instruction. They were asked to drive 30 - 35 km/h in the 30 km/h zones and 50 - 55 km/h in the 50 km/h zones. They were told to follow the course of the street. In this last section of the "training", two test scenarios were implemented (see *Additional scenarios* in Table 5.3). These were two scenarios with the possibility to anticipate the threat presented without a warning. After two harmless filler scenarios, all participants experienced the braking event and, after another harmless filler scenario, the scene with the pedestrian crossing the street was presented. This was done to facilitate the comparison between the "natural" behavior when the threat is anticipatable and the behavior later in the experiment, when the participants had learned that there is a FCW system on-board.

Table 5.3: Experimental Design

Main Situations					
		Warning Modality			
Type of threat	*Anticipation*	Acoustic	Haptic	Visual	None
Lead Vehicle brakes	possible	N=25	N=16	N=15	N=22
	not pos.	N=25	N=16	N=15	N=22
	wrong	N=25	N=16	N=15	N=22
Pedestrian crosses	possible	N=25	N=16	N=15	N=22
	not pos.	N=25	N=16	N=15	N=22
	wrong	N=25	N=16	N=15	N=22
Car takes ROW	possible	N=25	N=16	N=15	N=22
	not pos.	N=25	N=16	N=15	N=22
	wrong	N=25	N=16	N=15	N=22
Additional Situations					
LV brakes (Training)	possible	N=0	N=0	N=0	N=62
Ped X-ing (Training)	possible	N=0	N=0	N=0	N=62
LV brakes (1st warn)	not pos.	N=25	N=16	N=15	N=16

Pilot tests indicated that there might be a tendency for participants to wait for the warning even when the hazardous behavior of the other road user is predictable. After the training, there was a break and the participants had to answer a few questions about their driving habits and how confident they felt with the usage of the simulator setup (see Appendix, page 176). After that, the main part of the study started. The participants drove through the city for about 45 mins. All participants experienced the first warning in the same scenario: Lead vehicle braking, without anticipation. This scenario was repeated during the drive. The second time, the surroundings (parked cars, houses, pedestrians, etc.) as well as the color of the lead vehicle were changed to make it harder to recognize the scene. The layout of the street and the movements of the lead vehicle were kept the same. The order for all other scenarios was quasi-randomized. The rules for the order were as following:

- Two hazardous events shall not follow each other without at least one harmless scenario in between
- Two consecutive hazardous events shall not include the same type of threat
- The three warnings of one threat type shall not be presented in the first or last 15 modules, only

After finishing the 45 minute drive, the participants had a five minute break. Following that, the replication study was performed. The simulator and the three warnings of the urban city scenario explained in sections 5.2.1 and 5.2.2 were now used for all participants. The scenario and questionnaire were the same as in study one (cf. section 4.2). This time, three instead of ten warning types were compared and each warning was only displayed three times. As the time effects in Study One happened primarily between the first and second warning, a reduction to three reactions seemed reasonable. Hence the replication study took only 20 min. After this study part, every participant was paid 20 € as compensation.

5.2.5 Dependent Variables

Objective Data

The warning time is the reference time in all scenarios. For all analysis the warning time is set to zero. This means that all actions at a time < 0 happened before the warning and > 0 after the warning.
Several objective measures will be analyzed to answer different questions, as these objective measures are direct measures of, or results of driver behavior. Gas Reaction Time (GRT) and Movement Time are indicators for anticipative behavior. Early gas pedal release times and long movement times indicate anticipation of potential brake reactions. BRT is the most used measure for a driver's decision that a critical situation is evolving or that maintaining a safe distance is disrupted. Distance and TTC at braking onset are direct measures of criticality at the beginning of driver avoidance behavior. The time until brake maximum, maximal brake pedal velocity, and maximal deceleration can be interpreted as criticality assessment of the driver. Mean longitudinal deceleration point in the same direction, but shows an integrative value for the longer time frame of the complete avoidance maneuver. Direct measures of criticality are minimum distance, minimum TTC, and if a crash happened.

Subjective Data

After each target scene the participants where asked two questions. To collect data on how the participants judge the situation in regards of criticality, they were asked the question "How critical was the situation?". This judgment had to be made on a scale adapted from the Situation Criticality Scale by Neukum, Lübbeke, Krüger, Mayser, and Steinle (2008) (cf. 5.14). The adapted wording has been successfully used in a test track study before (Schmidt et al., 2009). The main advantage of this scale compared to often-used Likert scales, stems from the layout of the scale and the instruction. The participants have a clear cut criterion of what is acceptable for driving safety and traffic safety (< 7 scale points) and what is not (≥ 7 scale points). The participants are asked to pick a verbal category first and verbalize it. Then the participants refine their judgment with the numbers.

Figure 5.14: Situation Criticality Scale (translation from German original)

The second question asked was: "How satisfied are you with your performance?". This question has been shown to answer not only the apparent question but indirectly also the acceptance of an assistance system. The driver has to cooperate with the warning system and make the intervention himself. For reactions after the warning, the driver performance depends on the warning. Hence, this question allows the assumption that the warnings were accepted in these situations.
After the complete test, the participants in the warning groups were asked seven questions about the warnings and how the warnings changed their driving behavior (see appendix page 177).

Replication Study

The dependent variables for the replication study part in this study were the same as in Study One (cf. Section 4.2.6). The only difference is the gas pedal release time. In study one, before release, the pedal was in a constant position. In this study, the instruction allows any gas pedal position at any time. Therefore, gas pedal release times are only interpreted if the gas pedal was pressed before the dangerous situation. Further, because pedal positions cannot be assigned biunique to a reaction to the threat, the first time the gas pedal position is zero is analyzed.

5.3 Results

Due to data recording problems, 16 of the 79 participants can be analyzed in the Lead vehicle brakes scenarios only.

5.3.1 Main Analysis

The analysis is split for the three threat types: Lead vehicle brakes, another car takes the right of way and a pedestrian crosses the street. The threat types are fundamentally different and therefore analyzed separately. The main analysis deals primarily with the question of whether the different scenarios lead to different behavior of the participants and if the participants with the Forward Collision Warnings show different behavior than the control group. The data of each threat types is analyzed with an ANOVA for repeated measures and the data of the three warning modalities is merged into one group. If the main effect of the warning or the interaction (anticipation level $\times$ warning) is significant, the data will be reanalyzed to reveal potential differences caused by the warning modalities.
Through the study's instructions, participants were asked to drive at a speed of 50 - 55 km/h, but were allowed to choose a different speed. Therefore, a cut-off criterion was needed to analyze only comparable situations. Runs with speeds slower or equal to 45 km/h were excluded from the analysis. In Table 5.4, the number of analyzed data sets is shown. It is no surprise that the requested speed was not reached in the braking scenes more often than in the others. In the scenes with the pedestrian and the car that takes the right of way, the threat enters the scenes abruptly. The vehicle that stops in front of the participant is driving in front of the Ego-Vehicle for about 30s before it stops. Some of the participants obviously didn't want to follow the lead vehicle directly at the requested speed.

Table 5.4: Included Data Sets

	Lead vehicle brakes		
	Anticipation		
Warning	Possible	not Possible	Wrong
With	N=34	N=34	N=34
Without	N=13	N=13	N=13
	Pedestrian Crossing		
	Anticipation		
Warning	Possible	not Possible	Wrong
with	N=43	N=43	N=43
without	N=16	N=16	N=16
	Car takes the right of way		
	Anticipation		
Warning	Possible	not Possible	Wrong
with	N=44	N=44	N=44
without	N=15	N=15	N=15

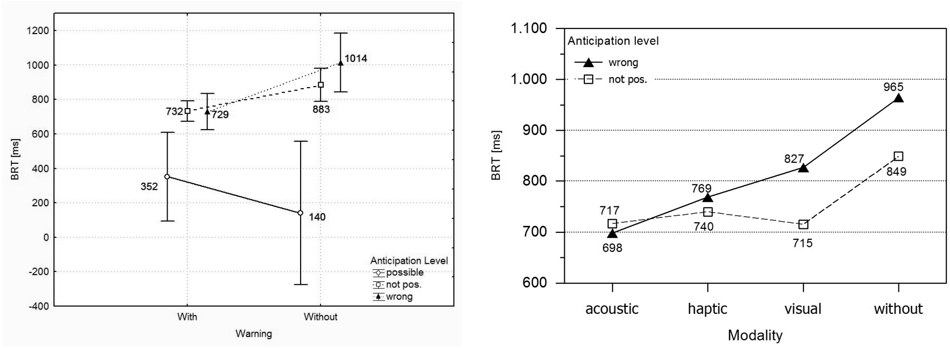
Table 5.5: Objective parameters from the scenarios "Lead vehicle brakes"

Parameter		Warning	Anticipation possible	not pos.	wrong
Velocity at BRT	km/h	With	51.98	53.16	52.16
		Without	52.30	53.29	51.94
Acc. pedal release time	ms	With	-789	180	143
		Without	-1003	281	210
Brake reaction time	ms	With	352	732	729
		Without	140	883	1014
Distance at BRT	m	With	24.40	22.63	22.89
		Without	24.82	21.21	19.78
Brake pedal position at 1st local maximum	%	With	56.00	77.00	77.00
		Without	43.00	66.00	65.00
Minimum TTC	s	With	1.50	1.32	1.37
		Without	1.40	0.79	0.67
Minumum Distance	m	With	9.56	7.41	8.29
		Without	8.97	4.95	6.64
Number of crashes	N	With	0.00	0.00	1.00
		Without	0.00	1.00	3.00

Lead Vehicle Brakes

Objective Measures The mean values of the objective measures for the analysis groups are presented in Table 5.5. Some results are additionally depicted in figures.
The velocity at braking onset is a criterion for exclusion because it is one parameter for comparable situations. All mean values lie between 51.89km/h and 53.89km/h (cf. Table 5.5). The small differences in-between the anticipation levels and the fact that a repeated measures ANOVA shows a difference only for the main effect of the factor "Anticipation" (df=2, f=43.2, $p<0.05$) give a basis for further analysis.

As pointed out earlier, the timing of the release of the accelerator pedal and the BRT are crucial measures for crash avoidance behavior. In the Lead Vehicle Brakes scenarios, the main factor Anticipation level is significant for the Accelerator Pedal Release Time (df=2, F=14.98, $p<0.00$) and the break reaction time (df=2, F=23.66, $p<0.00$). For both parameters, this results from the difference between the *possible* versus the *not possible* and the *wrong* level. With or without the warning, the participants react much earlier when the lead vehicle uses the turn signal. The main factor "Warning" does not show any significant effects. However, for the break reaction time the interaction of both factors shows a significant result (df=2, F=3.29, $p<0.05$).



(a) Main Analysis

(b) Sceanrio: Anticipation *Wrong* and *not possible*

Figure 5.15: Brake Reaction Time

Post-hoc Fisher LSD test reveals differences between several combinations of warning and anticipation levels and a tendency for the *wrong* anticipation level between with and without warning (p=0.06). For descriptive reasons, a One-way ANOVA for the warning modalities in this anticipation level was conducted. It shows a significant result for the factor modality (df=3, F=3.5, $p<0.05$). The means are depicted in Figure 5.15b. Post-hoc Fisher LSD test shows significant differences between the without group versus the acoustic and haptic warnings. There is more than 300 ms difference in mean reaction time between the acoustic and the without group. At a velocity of 50 km/h (13.89 m/s), the 300 ms reflects a distance of about 4 m. This is the length of a car and can make the difference between a crash and crash avoidance. These differences are extremely interesting because the participants from the without warning group lift their foot about 150ms later than the warning group. Then the warning group gains another 150 ms on the way to braking. Also in the Anticipation level *not possible* a one-way ANOVA was calculated for descriptive reasons. Here the modality also had significant impact on the BRT (df=3, F=3.01, $p<0.05$). Post-hoc Fisher LSD test shows differences on an alpha level of 5% between the without group and the acoustic and visual warning. The difference means the haptic group misses the 5% criterion marginal (p=0.56). The mean differences in this scenario are only about 130 ms, but the variance is low.

When looking at reaction times only, this misses the context in which the reaction took place. Table 5.6 and 5.7 show the percentage of participants who have either released the accelerator pedal or started to brake in a certain phase of the threatening situation. For both reactions, the situations are split into four phases (maximum). These phases can be associated with the classification suggested in the “Development of Research Question (see Fig. 2.27 and Table 2.9 on page 66). The first phase is always the constant

Table 5.6: Accelerator pedal release context

	Anticipation level		
	possible	not possible	wrong
Lead vehicle constant	4.76%	13.04%	8.77%
LV uses turn signal / Wrong threat appears	60.32%	n/a	5.26%
Lead vehicle brakes	0.00%	0.00%	8.77%
Warning issued	34.92%	86.96%	77.20%
Total	100.00%	100.00%	100.00%

Table 5.7: Brake Reaction Time context

	Anticipation level		
	possible	not possible	wrong
Lead vehicle constant	0.00%	0.00%	0.00%
LV uses turn signal / Wrong threat appears	19.04%	n/a	1.75%
Lead vehicle brakes	3.17%	0.00%	0.00%
Warning issued	77.77%	100.00%	98.25%
Total	100.00%	100.00%	100.00%

travel of the lead vehicle (combination 7 or 8 in Table 2.9). The second phase is only applicable to the Anticipation levels *possible* and *wrong*. It reflects the phase when the turn signal of the lead vehicle starts to flash or the wrong threat appears (also combinations 7 or 8). The third phase reflects the braking of the lead vehicle until the warning is issued (combination 3 or 4). The last phase starts with the warning or the point in time when the warning would have been issued (combination 1 or 2 with warnings, and 3 or 4 without warning). When anticipation is possible, more than 60% have lifted their foot off the gas and about 20% have already placed their foot on the brake in phase two (lead vehicle uses turn signal). When anticipation is not possible, 13% lifted their foot in phase one, most probably to regulate their speed. In the *wrong* level, a similar number of about 9% of the participants showed this. Another 14% start to react by lifting their foot in this level before the warning is issued. The biggest difference is observable in the brake reactions. When anticipation is possible, 1/3 of the participants are on the brake pedal befor the warning is issued, but for the other two situations everybody (except one) started to brake after the warning. This differences become very obvious when regarding the distance to the lead vehicle at braking onset (cf. Table 5.5). It has to be noted that the BRT and the distance to the lead vehicle at this time are highly correlated. The distance is only a consequence of the slower reaction, but it makes the effect very obvious. The ANOVA for repeated measures is significant for both main factors (Anticipation: df=2, F=22.22, $p<0.001$, Warning: df=1, F=5.31, $p<0.05$) and the interaction (df=2, F=5.66, $p<0.01$). Although there is no difference in the Anticipation *possible* level between the groups, the effect in the other two levels is so large that the warning has a positive impact on the distance as a whole. Amongst others, the post-hoc test shows differences between the control group and the warning group in the *wrong* situation. The measured difference between the groups' means is 3.11m. A descriptive look at the different modalities reveals similar effects as in the BRT data - significant, positive effects of the acoustic and visual warning versus the control group in the *wrong* situation and only a tendency for the difference of acoustic versus control group in the *not possible* situation.

Another behavioral impact of the independent factors can be observed in the first move of the participants' foot on the brake pedal. The numbers presented in Table 5.5 are first local maximum of the brake pedal position. It represents the intensity of the first movement of the brake pedal. The unit is the percentage of maximum pedal way of this participant. This parameter is suggested to be a behavioral indication of perceived criticality. If the participant depresses the brake pedal only for a small percentage in the first movement, it can be assumed that he does not judge the situation as highly critical. If, in contrast, he depresses the pedal fully in the first movement, one can interpret this as an evasive reaction to a highly critical rated situation. The percentages in the anticipation *possible* level are lower than in the other two. This difference is a significant result from the ANOVA for repeated measures for this parameter (df=2, F=4.69, $p<0.05$). Due to the high variance, the warning factor does not reach significance (df=1, F=1.50, p=0.22). As shown before, the brake reactions were done prior to the warnings in the *possible* level. Although the descriptives show a constant shorter first movement of the participants without the warning, this should not be interpreted regardless of the significance. When taking a closer look at the data, it can be seen that this difference mainly stems from the haptic warning group which tends to react with stronger first brake pedal movements, regardless of the anticipation level. Additionally, it has to be highlighted again that the simulator setup used a gaming control for driver inputs. Therefore, the break pedal counterforce was unrealistically low. Hence, transfers to behavior in real traffic in real cars is limited.

A very interesting parameter of course is the minimum time to collision (TTC) during the event (also Table 5.5, page Table 120). In this,it is striking that the minimum TTC for the participants with warnings does not differ a lot between the different anticipation levels. The means go from 1.32 to 1.50s. But the differences of the control group are big. The lowest mean value was measured for the control group in the anticipation level *wrong*. The ANOVA revealed significant results for both main factors and the inter-

Table 5.8: Repeated Measures ANOVA for minimum TTC

Effect	df	F	p
Warning	1	4.92	0.03
Anticipation	2	10.72	0.00
AP × Warning	2	4.68	0.01

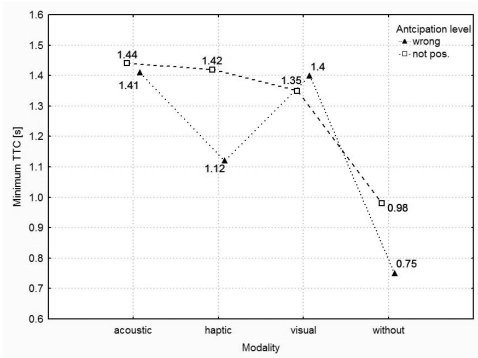


Figure 5.16: Minimum TTC for modalities in Anticipation levels *wrong* and *not pos.*

action (cf. Table 5.8). As the data is most interesting for the anticipation *not possible* and *wrong* levels, this data is depicted in Figure 5.16. A desriptive look at the data shows similar data for all conditions with warnings and shorter TTCs for the control group. Only for descriptive reasons two one-way ANOVAS for each scenario have been calculated. In both cases the result is a marginal significance (not pos.: df=3, F=2.42, p=0.07; wrong: df=3, F=2.38, p=0.08). When looking at the mean values, these differences most probably stem from the acoustic and haptic versus the without group in the *not possible* scenario and the acoustic and the visual versus the without group in the *wrong* scenario. This shows that drivers without any warning get the smallest TTC values especially in the wrong condition, but it is a constant main effect. The absolute minimum distance is an interesting value, because it shows how close a crash has been. When looking at the mean values in Table 5.5, one can see that the majority of drivers came to a stop at a safe distance between 5 and 10m. Although the descriptive data suggests an influence of the warning, the repeated measures ANOVA does not reveal one (df=1, F=1.85, p=0.18). But again, the main effect of the Anticipation level shows a significant effect (df=2, F=8.69, p<0.001). Post-hoc tests show a difference between the Anticipation level *possible* versus *not possible* and *wrong*. Interestingly, the descriptive data shows that the mean values of the minimum distance in the level *not possible* is smaller than in *wrong*. But in the rest of the data there is no hint that the *not possible* scene was more dangerous. Although the majority of the participants stopped at a safe distance, five crashes happened in these scenes (cf. Table 5.5). Four happened without a warning, but only one with the warnings. The occurrences are too few to calculate any inferential statistics.

Subjective Measures Very important measures are the subjective assessments of a situation. How does the participant experience the situation? Does it change with a (certain) warning? As explained in Section 5.2.5 the subjective criticality was queried after each situation as well as the question "How satisfied are you with your performance?". Earlier studies have shown that this question also gives an integrative answer on actual performance and information on the acceptance of the assistance. The results of the answers to the criticality question are shown in Figure 5.17. The solid, grey lines mark the changes in the verbal categories. Altogether the scenarios with the braking lead vehicle have been judged from "harmless" to "uncomfortable". Quite striking is that the different AP levels have only a minor effect on the warning group but a bigger one on the control group. When the AP is possible both groups judge the situation as harmless (approx. 3). For the warning group this value changes almost unnoticeably for the other two AP levels. On the other hand, without a warning the AP not possible scene is judged as uncomfortable (4.17) and the AP wrong as uncomfortable (5.33). This is also reflected in the ANOVA. Both main factors and the interaction are significant with a p-level of 0.05 and the factor Anticipation even on a p-level of 0.001. Most interestingly is the interaction. A Fisher post-hoc test reveals that the data from the control group in the AP wrong scene differs to all other factor combinations. Additionally the control group with AP not possible is different to both groups in the AP possible scene. With this result, the data is analyzed for modalities (cf. means in Figure 5.18). From the descriptive data, the acoustic and the visual warning lead to the least critical judgments. For the haptic and the control group the differences between the three AP levels is clearer, but the order of the AP levels for the criticality judgments is the same for all modalities.
The performance assessment shows similar results (cf. Figures 5.19 and 5.20). This time the influence of the warning factor is more distinct as in the criticality judgment. Both factors as well as the interaction are significant on a 1% p-level. The LSD post-hoc test of the interaction reveals that the judgment for no warning and AP wrong is different to all other data points. The same is true for the with warning, AP possible data with the exception that the difference to no warning, AP possible is only a tendency. Because of the significant results, this data is also split for modalities as depicted in Figure 5.20. Across all AP levels there is a downward tendency for the experienced performance starting best with the acoustic warning, than the haptic, the visual and worst without a warning. What do the participants build their judgment about their performance on? It would be interesting if

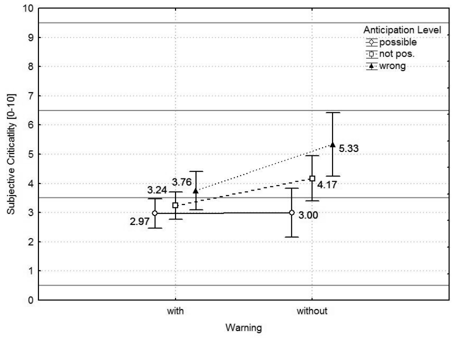


Figure 5.17: Subjective Criticality, LV brakes

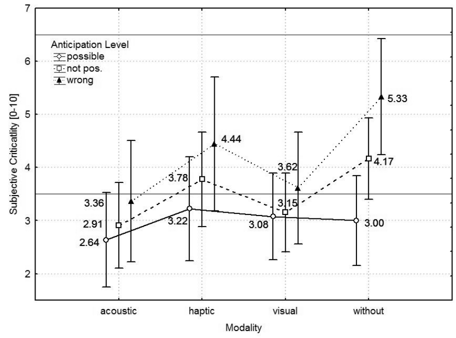


Figure 5.18: Subjective Criticality split for Modalities, LV brakes

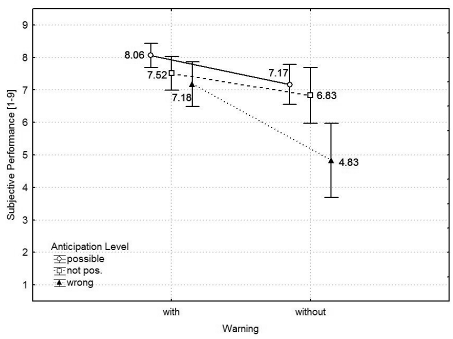


Figure 5.19: Subjective Performance, LV brakes

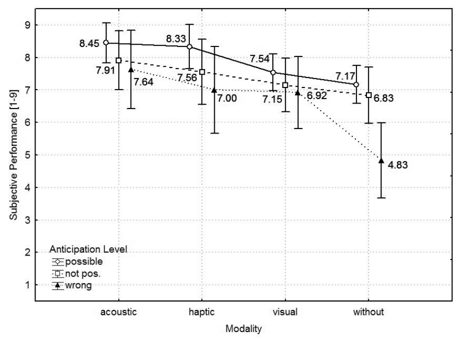


Figure 5.20: Subjective Performance split for Modalities, LV brakes

Table 5.9: Bivariate Correlations for minimum TTC and subj. Performance, LV brakes

			Performance		
	AP		possible	not pos.	wrong
TTC min	possible	r	*.275	.116	.297
		p	.048	.422	.063
	not pos.	r	.233	**.409	.197
		p	.115	.002	.223
	wrong	r	.372*	.344*	**.688
		p	.017	.022	.000

p is two-tailed and significant correlations are flagged

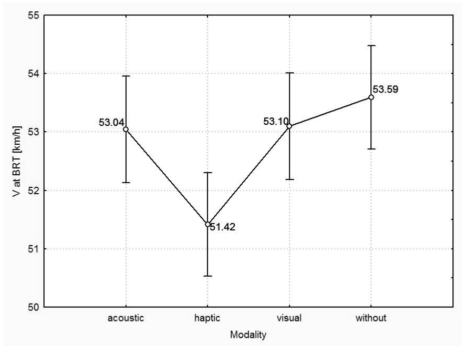


Figure 5.21: V at BRT in Anticipation level *wrong*

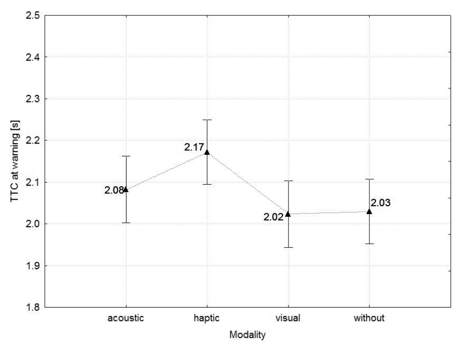


Figure 5.22: TTC at warning in Anticipation level *wrong*

this could be linked to objective measures. As explained in the theoretical background, most of the FCWS use the TTC for the decision to warn. Hence the correlation between minimum TTC and subjective performance was analyzed (cf. Table 5.9). The correlation is significant for every AP level, but it is stronger for the AP situations *not possible* and *wrong*. For the wrong situation, the dependency is strong with an R = 0.688. As the correlation is positive, this means the lower the minimum TTC was during a situation, the less satisfied the participants were with their performance. It seems that the participants based their judgment on the minimum TTC.

Regarding the subjective statements in the lead vehicle braking scenarios, the warnings lead to less critical situations and better performance - especially if the anticipation is misled by another threat. The acoustic warning is rated best overall.

Pedestrian Crosses the Street

Objective Measures The mean values of the objective measures are presented in Table 5.10. Some measures are additionally depicted in Figures. The criterion velocity at the beginning of braking differs between the warning and the control group (cf. 5.10). This was not expected. Although the mean difference is not big (warning = 52.14km/h vs. no warning = 53.27km/h) it becomes significant in a repeated measures ANOVA (main factor Warning: df=1, F=8.02, $p<0.01$). When looking into the data for the individual Anticipation levels the difference is most prominent in the Anticipation level *wrong*. A descriptive analysis of the mean values of the different modalities in Figure 5.21 shows that this difference results from a lower speed of the haptic warning group.

For the evaluation of further data, it is of interest if the time to collision (TTC) at the point in time the warning was issued differs. The TTC differs prominently in the AP condition *possible* (cf. 5.10). Because of the

Table 5.10: Objective parameters from the scenarios “Pedestrian crosses the street”

Parameter		Warning	Anticipation possible	not pos.	wrong
Velocity at BRT	km/h	With	52.17	51.88	52.39
		Without	53.10	52.96	53.75
TTC at T0	s	With	2.56	2.19	2.11
		Without	2.00	2.10	2.02
Acc. pedal release time	ms	With	-2078	159	-61
		Without	-2189	281	208
Brake Reaction Time	ms	With	-1210	616	616
		Without	-1000	579	713
Brake pedal position at 1st local maximum	%	With	23.58	71.35	75.37
		Without	27.64	78.12	74.61
Minimum TTC	s	With	1.96	1.14	1.21
		Without	1.78	1.14	0.80
Minumum Distance	m	With	11.65	5.61	6.13
		Without	10.50	5.65	3.50
Number of crashes	N	With	0.00	2.00	2.00
		Without	0.00	1.00	2.00

speed difference at braking onset differed for the warnings in AP *wrong*, the means are also displayed for this condition in Figure 5.22. Again the haptic group has slightly higher values. Just as a reminder - the warning could not have an influence as it had not been displayed at that moment. Hence, in the further presentation of the results it has to be considered that the speed was slower and TTC was higher for the warning group. This only effects distance related measures as minimum TTC, distance and number of crashes. The mean values of the accelerator pedal release time are depicted in Figure 5.23. When analyzing this data, there is a significant effect of the Anticipation level (df=2, F=72.27, $p<0.001$), but no effect of the warning or the interaction. When the pedestrian is visible for some time before it gets critical (AP *possible*), the participants release the accelerator pedal about 2s before the warning. In the other two conditions this reaction is shown around the time the warning is issued. In the wrong condition, participants with the warning lift their foot slightly earlier than the warning and seem to have reacted to the wrong threat. It is noteworthy that the difference between the with and without warning group is not significant (p=0.67).
That stays the same for the Brake Reaction Time. The Anticipation level is highly significant (df=2, F=254.29, $p<0.001$) but the warning or the interaction has no effect. Even the alleged advantage of the warning group having the foot lifted in the wrong condition is eliminated. The mean value is 616ms in both situations. This suggests that the participants really watched the wrong threat and that the advantage is lost because of that in comparison to the *not possible* situation.
The two reactions are shown in relation to the context in Tables 5.11 and 5.12. Again, the phases reflect combinations from Table 2.9. The clear distinction between the Anticipation *possible* and the other two is reflected. In the *possible* situation, 97% of the participants lift their foot during the time the pedestrian is on his way towards the street, and 88% of them even brake in that phase (combination 7 or 8). In the other two situations it is more or less the other way around. Ninety-two percent or respectively 81% of the participants released the accelerator pedal in these situations after the warning was / would have been issued (combination 1 or 2 with warning, 3 or 4 without). Interestingly, 16% lifted their foot before the real threat was visible in the *wrong* condition. This emphasizes the idea that the participants watched the wrong threat. All participants started to brake after the point in time when the warning was / would have been issued in the *wrong* and *not possible* conditions. The difference between the anticipation levels is also distinct in the parameter of the first local maximum of brake pedal travel (cf. 5.10). In the scenarios, when the real threat is visible for a long time, the participants press the brake pedal down onlyto about 20 to 30% of the maximum way. In the AP levels *not possible* and *wrong*, the mean value of the first local maximum is higher than 70%. This difference of the factor Anticipation is significant in the repeated measures ANOVA

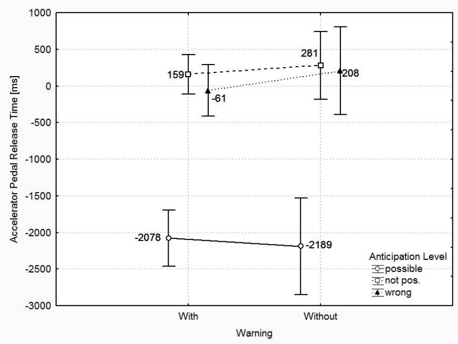


Figure 5.23: Accelerator Pedal Release Time

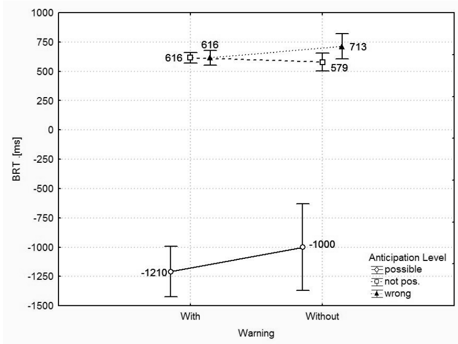


Figure 5.24: Brake Reaction Time

Table 5.11: Accelerator release time context, Pedestrians

	Anticipation level		
	possible	not possible	wrong
Pedestrian visible/			
Wrong threat visible	97%	3%	16%
Pedestrian steps on street	0%	5%	3%
Warning issued	3%	92%	81%
Total	100%	100%	100%

Table 5.12: Brake Reaction Time context, Pedestrians

	Anticipation level		
	possible	not possible	wrong
Pedestrian visible/			
Wrong threat visible	88%	0%	0%
Pedestrian steps on street	5%	0%	0%
Warning issued	7%	100%	100%
Total	100%	100%	100%

(df=2, F=33.13, p<0.001). This data suggests a controlled braking process for the Anticipation *possible* scenes and a surprised reaction for the other two scenarios.
As noted in the beginning of this chapter, the minimum TTC and the other distance related parameters have to be interpreted cautiously because the control group entered the scene with a higher speed and a lower TTC at the time of the warning. The difference was highest in comparison with the haptic warning group for the *wrong* scenes. Because the warning modality could not have an impact at that time, the haptic group is post hoc excluded from the analysis of the distance related measures. The mean values of the minimum TTC and minimum Distance are also presented in Table 5.10 on page 128. Naturally, both parameters are highly correlated and show a similar result. The descriptive data shows a clear difference between the AP level *possible* and the other two. With a warning, the difference between not possible and wrong is small, while in the wrong condition the unwarned participants reach more critical values. For the inferential statistic analysis it is inappropriate that the warning group has higher values in the *possible* scenarios than the without group. Because of that, the influence of the warning would be overestimated. Hence the inferential statistic analysis is reduced to the AP levels *not possible* and *wrong*. The ANOVA for repeated measures of the minimum TTC reveals a strong tendency for the AP level (df=1, F=3.79, p=0.057) although the level *possible* was not part of the analysis. The warning also shows a tendency (df=1, F=3.13, p=0.08), while the interaction does not influence the minimum TTC (p=0.17).
Also the ANOVA for the minimum distance is conducted for the conditions *not possible* and *wrong* only - both without the haptic group. The AP level shows a tendency (df=1, F=3.20, p=0.08) and the warning is not significant (df=1, F=2.53, p=0.11). The interaction of both factors also does not influence the minimum distance (df=1, F=1.36, p=0.24). The impression from the mean values is validated only partly: The not possible scenario leads to higher distances and TTCs than wrong, and drivers without the warning end up in slightly more critical situations. The total number of crashes in this type of scenario was seven. (The haptic group is included for the sake of completeness.) The distribution over the different scenarios and warning groups is captured in Table 5.13. As the total number is so low, this data is only presented descriptively. No-one with an acoustic warning hit the pedestrian. Although the haptic warning group had a lower speed in the beginning in the mean value, one of the participants crashed. In the *not possible* situation one participant and in the *wrong* situation two participants couldn't stop early enough with the visual warning as well as without a warning.

In the subjective judgment about the criticality of the situation, the participants make a clear distinction between the AP *possible* level versus the

Table 5.13: Number of Crashes, Pedestrians

	Warning			
AP Level	acoustic	haptic	visual	without
possible	0	0	0	0
not. possible	0	1	1	1
wrong	0	0	2	2
Total	0	1	3	3

AP levels *not possible* and *wrong*(cf. 5.25). The distribution of judgments per category are listed in Table 5.14. This shows that the situation anticipation *possible* was judged by 75% to 81% of the participants as “harmless”. The other situations are mainly rated as “uncomfortable” or “dangerous”. The AP *wrong* situation, especially, is only rated as “harmless” by 6% of the control group. These differences also manifest in the results of the repeated measures ANOVA. The AP level and the warning group have significant effects on the judgments (AP level: df=1, F=43.7, $p<0.001$; Warning: df=1, F=5.03, $p<0.05$). With a warning, the participants rate the situations as less critical. As the warning factor is significant, the data is also split for modalities (cf. Figure 5.26). The graph shows that there are no drastic differences between the modalities. As only the main factor warning was significant in the first analysis, the different AP levels are only shown for descriptive reasons. There is a tendency (p=0.09) in a LSD post-hoc test of the modality for differences between the acoustic and visual group versus the control group. The acoustic and visual warning group rates the situation less critical than the group without a warning.

Subjective Measures Figure 5.27 shows the mean values for the subjective assessment of the participants’ performance. There is a clear distinction between the AP levels. The performance is rated best in level AP *possible* and worst in AP *wrong*. This difference is also found on a p-level of 0.01 in the repeated measures ANOVA. The chart also shows lower ratings for the control group. This difference is supported only by a tendency in the ANOVA (df=1, F=3.4, p=0.07). The interaction does not have an effect. When looking at Figure 5.28, it is interesting that with the acoustic and haptic warnings the performance judgment does not change between AP *not possible* and *wrong*, but with the visual warning and in the control group the performance is rated lower in the *wrong* condition.

As in the “Lead Vehicle Brakes” scenario, the correlation between the subjective criticality and the minimum TTC is analyzed. For this analy-

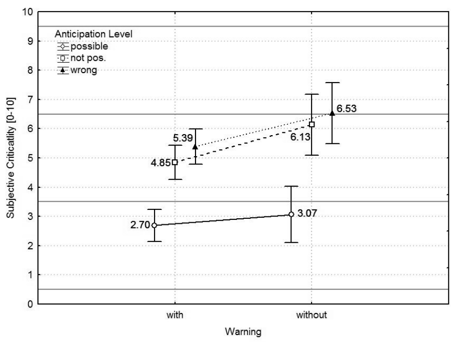


Figure 5.25: Subjective Criticality, Ped X-ing

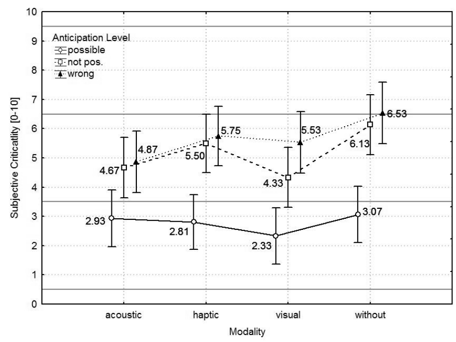


Figure 5.26: Subjective Criticality, split for modalities, Ped X-ing

Table 5.14: Percentage of Criticality categories for Pedestrian X-ing Scenes

		AP possible		AP not pos.		AP wrong	
Category		with	without	with	without	with	without
crash unavoidable	[10]	2%	0%	0%	0%	2%	0%
dangerous	[7-9]	4%	0%	26%	46%	33%	50%
uncomfortable	[4-6]	13%	25%	43%	20%	46%	44%
harmless	[1-3]	79%	75%	31%	34%	19%	6%
free driving	[0]	2%	0%	0%	0%	0%	0%

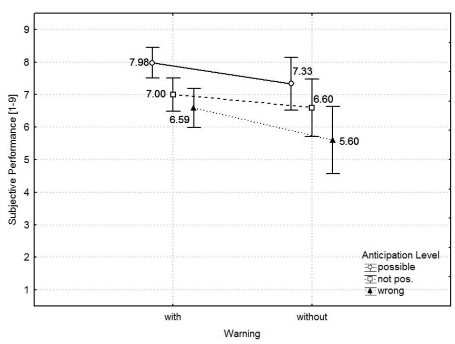


Figure 5.27: Subjective Performance, Ped X-ing

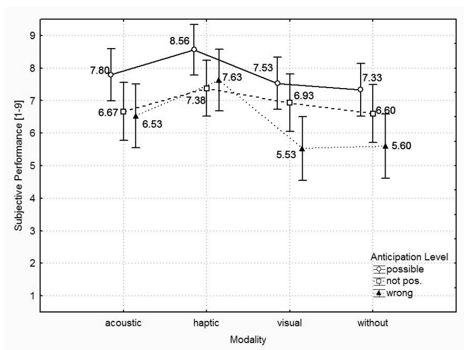


Figure 5.28: Subjective Performance, split for modalities, Ped X-ing

Table 5.15: Bivariate Correlations for minimum TTC and subj. Performance, Ped X-ing

			Performance		
	AP		possible	not pos.	wrong
TTC min	possible	r	**.451	.176	.023
		p	.000	.190	.862
	not pos.	r	-.083	**.517	-.135
		p	.532	.000	.299
	wrong	r	.044	.076	**.395
		p	.737	.559	.001

p is two-tailed and significant correlations are flagged

sis, the haptic group is included as the proposed influence of the minimum TTC on the subjective criticality is not detracted from the unequal starting conditions. As in the lead vehicle brakes scenario, there is a significant correlation between the performance ratings and the minimum TTC (see Table 5.15). The correlations are not as strong as in the other scenario but still significant.

Vehicle Takes Right of Way

As long as the threat is not visible, the three scenes are technically similar. There is no car in front and the street is straight for at least more than 500m. When looking at the speeds at the beginning of braking in Figure 5.29, the without warning group appears a little faster (approx. 1.5km/h) than the warning group. But the velocity is not significantly different (cf. Table 5.17). Nonetheless, all the factors and the interaction show a tendency. When taking a closer look in the *wrong* data, a similar pattern as in the pedestrian scenes is recognizable. The haptic group is slower than the others and the control group is faster. When comparing the distance at the T0 when the warning is issued and the TTC at that time in Table 5.16, it can be seen that the velocity difference at BRT has only a minor influence on these values. The mean values for the distance differ 39cm and for the TTC of 0.07s. As the speed difference is not significant and the critical parameters as distance and TTC at warning onset are influences only marginally, all data is included in the following analyses.

The accelerator release time, as shown in Figure 5.30, shows a distinc-

Table 5.16: Baseline measures in the anticipation level *wrong*

Parameter		Modality audible	haptic	visual	w/o
Velocity at BRT	km/h	52.59	52.00	52.89	54.09
Distance at T0	m	13.89	14.12	14.08	13.73
TTC at T0	s	0.95	0.98	0.69	0.91

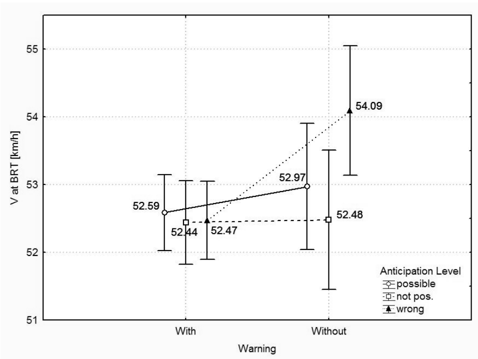


Figure 5.29: Mean Velocities

Effect	df	F	p
Warning	1	3.28	0.08
Anticipation	2	2.54	0.08
AP × Warning	2	2.57	0.08

Table 5.17: Repeated measures ANOVA

tion between the AP Levels, but is not influenced by the warning. This is also reflected by the repeated measures ANOVA, which shows a highly significant effect of the factor Anticipation only (df=2, F=16.04, p<0.001). The BRT mean values in Figure 5.31 are clearly divided between the AP level *possible* and the other two. An influence of the warning is not detectable. This observation is reflected by the repeated measures ANOVA, which shows a significant effect from the AP level (df=2, F=109.12, p<0.001). Interestingly, the potential advantage in the AP *possible* versus the *wrong* situation is the accelerator pedal release time of about 500ms shrinks to circa 50ms in the BRT. Because the participants' reaction times were not altered by the warnings, the data suggests that the participants rather reacted to the threat. There is no difference between the warning groups. The general statements regarding the context of reaction times can also be seen in the Tables 5.18 and 5.19. The parameter distance at BRT shows the same dependencies on AP and warning as the BRT. The warnings had no positive influence even with a slightly better start regarding the distance at T=0. Although the AP level is highly significant (df=2, F=82.77, p<0.001). Also for the first local maximum of the brake pedal position, the difference between the AP levels is distinct. This effect is significant in the ANOVA (df=2, F=25.48, p<0.001), but the warning factor as well as the interaction is not (p>0.5). Although the descriptive data for minimum TTC and distance (cf. 5.20) suggests a difference between the warning groups for the AP level wrong situation for

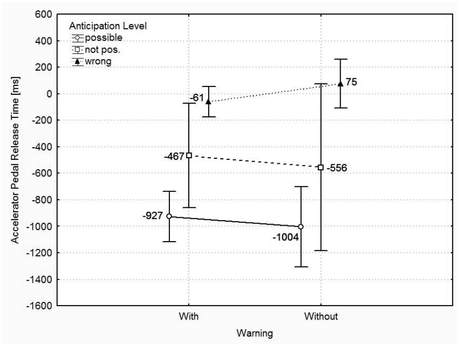


Figure 5.30: Accelerator Pedal Release Time

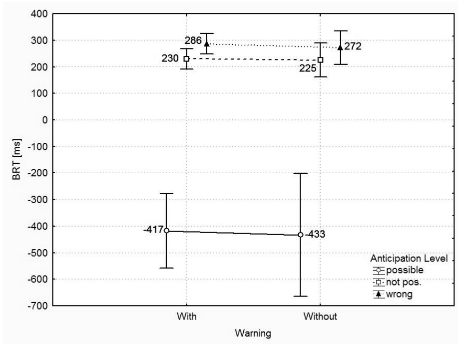


Figure 5.31: Brake Reaction Time

Table 5.18: Accelerator release time context, Car Takes ROW

	Anticipation level		
	possible	not possible	wrong
Obvious threat visible/			
Wrong threat visible	84%	20%	11%
Car Takes ROW	13%	23%	10%
Warning issued	3%	57%	79%
Total	100%	100%	100%

Table 5.19: Brake Reaction Time context, Car Takes ROW

	Anticipation level		
	possible	not possible	wrong
Obvious threat visible/			
Wrong threat visible	31%	0%	0%
Car takes ROW	51%	0%	0%
Warning issued	18%	100%	100%
Total	100%	100%	100%

Table 5.20: Objective parameters from the scenarios “Car takes Right of Way”

Parameter		Warning	Anticipation possible	not pos.	wrong
Acc. pedal release time	m	With	-927	-467	-61
		Without	-1004	-556	75
Brake Reaction Time	m	With	-417	230	286
		Without	-433	225	272
Distance at BRT	m	With	20.37	12.03	11.15
		Without	20.57	12.11	10.79
Brake pedal position at 1st local maximum	%	With	55.00	88.00	94.00
		Without	52.00	77.00	95.00
Minimum TTC	s	With	1.11	0.71	0.66
		Without	1.03	0.71	0.57
Minumum Distance	m	With	10.20	7.20	6.62
		Without	9.46	7.18	5.63

both parameters, neither the warning nor the interaction shows a significant effect in the repeated measures ANOVA. The AP factor becomes highly significant for both (TTC: df=2, F=39.35, $p<0.001$, distance: df=2, F=32.69, $p<0.001$).
There have been no crashes in any of the Car takes ROW scenes.

Subjective Measures The subjective evaluation of the situations is different than of the other two threat types. The criticality of the situations is higher in total and the AP *possible* situation is not considerably lower than the rest (cf. Figure 5.32). More than 40% of the participants rated the events higher than 7 and, therefore, as “dangerous”. The ANOVA shows a significant difference between the AP levels (df=2, F=18.03, $p<0.001$), but no other significant effect. The post-hoc Tukey test on AP levels shows significant differences between all levels on a p-level of 1%.
The participants rated the question “How satisfied are you with your performance?” (cf. Figure 5.33) highly. There is no statistically relevant effect from one of the factors or the interaction. The total mean of the performance rating is 6.90. That means they are “very” satisfied with their performance. When looking at the correlation between the performance and the minimum TTC in Table 5.21 there is no significant dependency. One explanation could be that the suddenly appearing threat created a very critical event (see Figure 5.32) and the subjects were content to have avoided an accident. The minimum TTCs were exceptionally low, but no accident occurred. Hence,

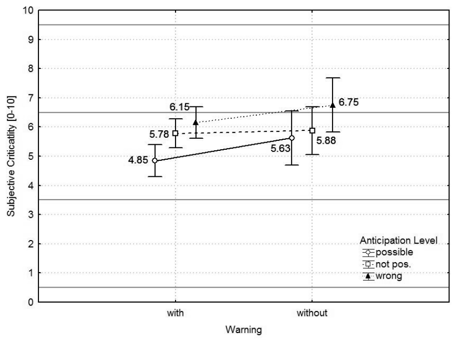


Figure 5.32: Subjective Criticality, Car takes ROW

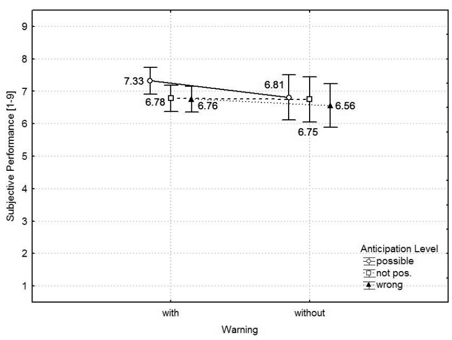


Figure 5.33: Subjective Performance, Car takes ROW

Table 5.21: Bivariate Correlations for minimum TTC and subj. Performance, Car takes ROW

			Performance		
	AP		possible	not pos.	wrong
TTC min	possible	r	.064	-.120	-.152
		p	.631	.372	.254
	not pos.	r	-.121	.058	-.096
		p	.356	.659	.461
	wrong	r	.098	.037	.125
		p	.456	.781	.336

p is two-tailed and significant correlations are flagged

they all rated their performance as very good.

Concluding subjective assessment of the warnings

As an overview on how the participants judged the warnings at the end of the drive, Table 5.22 presents the answers. These questions had to be answered on a 6-point-scale ranging from "not at all" (0) to "very much" (5). The effects of the warning modalities on the answers have been analyzed with a one-way ANOVA. In Table 5.22, the degrees of freedom, the F-statistic, and the p-value are given for each question. For the results, it has to be considered that there was no suppression algorithm implemented. That means, even if a participant reacted earlier than the warning trigger, a warning was issued.

In general it can be stated that all warnings have been judged fairly well. All warnings are judged as easily comprehensible (mean = 4.2). The participants say that they were fairly supported by the warnings (mean = 3.48). The participants state that the warnings did distract them (mean = 1.17) and annoyed (mean = 1.30) them only a little. The annoyance question revealed only a significant difference between modalities. A post-hoc Tukey test reveals that the difference occurs between the visual and the haptic warning group, whereas the haptic group was annoyed more than the visual group. The participants relied "much" on the warnings (mean = 3.76). As there had been no false positive warnings, the reliance is based on good cause. The participants state that they had not been driving any more riskily than without the warning (mean = 0.7) and that it made their driving safer by "a little" to a "medium" amount(mean = 2.52).

5.3.2 First Warning Analysis

The following analysis should clarify if there is a difference between a situation where the warning is issued a first time and when the driver knows about the system. Because the participants did not know that a FCW system was on board, the first scene with a warning acted as a "Surprise trial".

Immediately after the surprise event, the participants were asked an open answer question about what they think the tone, visual display, or seat vibration meant. Without knowledge of the system, 77% of the participants correctly identified the warnings as a Forward Collision Warning. Altogether 44 participants were asked this question. There was no difference regarding the warning modalities (cf. 5.23).

Objective Data Analysis

As inferential statistics tests repeated measures, ANOVAs were calculated for all parameters. The mean values for the objective parameters are presented in Table 5.24.
The first analysis is a look at the velocity at the beginning of braking as it is depicted in. The descriptive impression that there is a difference between the trial is proven by the ANOVA (df=1, F=4.08, $p<0.05$). The mean difference is 0.73km/h. There is no effect by the warning group or the interaction. For further analysis, the slightly higher speed in the surprise trial has to be kept in mind.
The point in time when the accelerator pedal is released by the participants is not influenced by any tested factor. The mean values in the Surprise trial show later reactions than later in the experiment, but as just stated, this

Table 5.22: Assessment of Warnings

Variable	Modality	N	Mean	St. Dev	df	F	p
Supported	Acoustic	15	3.40	1.183			
	Haptic	16	3.56	1.263			
	Visual	15	3.47	1.246			
	Overall	46	3.48	1.206	2	.068	.934
Comprehensible	Acoustic	15	4.07	1.033			
	Haptic	16	4.25	.856			
	Visual	15	4.27	.594			
	Overall	46	4.20	.833	2	.259	.773
Distracted	Acoustic	15	1.33	1.291			
	Haptic	16	1.25	1.483			
	Visual	15	.93	1.033			
	Overall	46	1.17	1.270	2	.405	.670
Annoyed	Acoustic	15	1.27	1.163			
	Haptic	16	1.94	1.389			
	Visual	15	.67	.976			
	Overall	46	1.30	1.280	2	4.403	.018
Relied	Acoustic	15	3.87	.915			
	Haptic	16	3.63	1.500			
	Visual	15	3.80	.941			
	Overall	46	3.76	1.139	2	.181	.835
Riskier	Acoustic	15	.87	.834			
	Haptic	16	.63	.806			
	Visual	15	.60	.828			
	Overall	46	.70	.813	2	.485	.619
Safer	Acoustic	15	2.33	1.175			
	Haptic	16	2.63	1.628			
	Visual	15	2.60	1.502			
	Overall	46	2.52	1.426	2	.188	.829

Table 5.23: Identification as FCW

Identified	Acoustic	Haptic	Visual	Total
Correctly	11	11	12	34
Wrong	4	3	3	10
Total	15	14	15	44

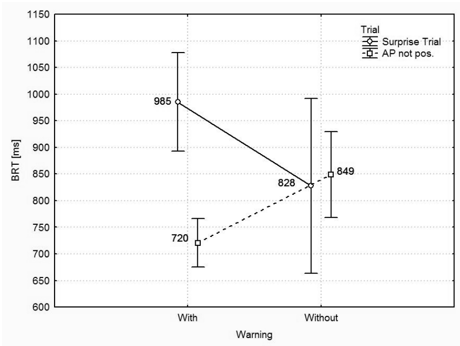


Figure 5.34: Brake Reaction Time, Surprise vs. later

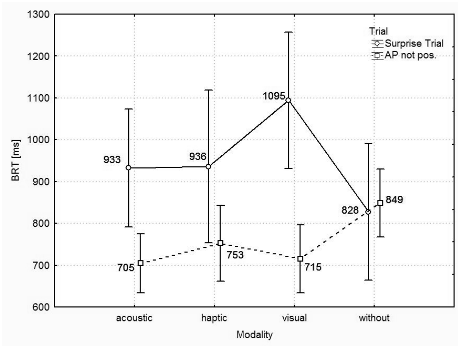


Figure 5.35: BRT split for modalities, Surprise vs. later

difference can not be statistically validated.

The main parameter Brake Reaction Time shows another picture (cf. Figure 5.34). There is no difference between the two trials in the without warning group. But with warnings the trial makes a difference. The ANOVA shows a significant effect of the trial (df=1, F=5.69, $p<0.05$) as well as the interaction (df=1, F=7.84, $p<0.01$). The Fisher post-hoc test in Table 5.25 revealed significant differences between the Surprise trial with a warning and later in the experiment. But it also differed in the surprise trial to the no warning group and there is a tendency to the AP *not possible* situation. When coming in contact with the warning the first time, the reaction is slowed down. When the warning is known to the driver, it speeds up the driver's brake reaction. And, on the other hand, the control group proves that there is no time or learning effect, because the reaction times of the control group stays the same. This suggests that the participants are distracted or irritated by the first time warning. Because of the significant interaction effect, the data is also analyzed split for warning modalities. The mean values are depicted in Figure 5.35. The data supports the distraction hypothesis because the participants with the visual warnings especially have the slowest reaction times. Interestingly, this difference vanishes in the AP *not possible* scenario and all warnings lead to faster reaction time than without a warning. For descriptive reasons another repeated measures ANOVA has been calculated with the factors Trial and Modality. As in the condensed analysis the Trial becomes highly significant on a p-level of 0.001 and the interaction is significant, too ($p=0.02$). The Fisher post-hoc test shows that the visual warning in the surprise trial is the only value that is significantly slower than the control group. The acoustic warning shows a tendency to be faster than without a warning in the AP not possible condition ($p=0.09$). Therefore, one result is that a visual warning slows the reaction down when the warning is unknown to the driver, whereas an acoustic warning facilitates the reactions when the warning is known to the driver.

Table 5.24: Objective parameters surprise trial vs. anticipation not possible later in the experiement

Parameter		Warning	Trial Surprise	 AP not pos.
Velocity at BRT	km/h	With	53.01	52.47
		Without	53.45	52.44
Acc. pedal release time	ms	With	324	170
		Without	519	263
Brake Reaction Time	m	With	985	720
		Without	828	849
Distance at BRT	m	With	22.89	19.61
		Without	21.71	21.02
Brake pedal position at 1st local maximum	m	With	69.20	74.90
		Without	75.70	66.00

Table 5.25: BRT interaction, Fisher Post-hoc test

	Warning	Trial	1	2	3	4
1	With	Surprise		0.00***	0.04*	0.07
2	With	AP not pos.	0.00***		0.15	0.08
3	Without	Surprise	0.04*	0.15		0.81
4	Without	AP not pos.	0.07	0.08	0.81	

Table 5.26: Percentages of Crashes for Surprise trial and AP not pos. when LV brakes

Trial	Acoustic	Haptic	Visual	Without
Surprise	13%	15%	40%	7%
AP not pos.	0%	0%	0%	6%

The distance at the point in time when the participant presses the brake the first time reflects exactly the results of the BRT itself. Therefore it will not be discussed further (cf. 5.24). Neither the warning nor the trial factor has an impact on this parameter. In all conditions, the participants depress the pedal at around 70% with their first movement. This value seems to be typical for this simulator setting and unexpected threat.
The different reaction times do have an effect on the minimum distance to the lead vehicle in these scenarios (see Figure 5.36). The different speeds at BRT could make a difference here, but in the no warning group, the minimum distance does not differ. In the warning group, the mean value is doubled from the surprise trial to the trial later in the experiment. These big differences also become significant in the ANOVA. There is a significant effect by the Trial (df=1, F=7.85, $p<0.01$), which can be explained completely by the interaction (df=1, F=7.57, $p<0.01$). The analysis split for modalities reflects most of what was shown by the results of the BRT. In Figure 5.37, the close distances of the visual group in the surprise trial can be seen. In the Fisher post-hoc test, the distance of the visual group in the surprise trial is significantly different to all data points except the acoustic group in the surprise trial. This is surprising because the acoustic group had the shortest BRT. When comparing the furthest distances to the control group, only the acoustic warning is significantly different (p=0.04), but the haptic group shows a clear tendency (p=0.06). For this parameter, the acoustic and the haptic warning lead to the safest results, when the warning is known to the driver. If it is not known to the driver, these warnings do not help. Worse is the visual warning: When drivers do not know about the presence of the warning it leads to close distances. Half of what participants encounter without a warning. This resulted in 13 crashes altogether for the two scenarios (12 for the surprise trial, 1 for AP not possible). Half of the crashes in the surprise trial were caused by participants with a visual warning. The percentage distribution is listed in Table 5.26. At the surprise trial, 6 of 15 (40%) participants with the visual warning crashed, whereas only 7% crashed without a warning. This could lead to a statement that a visual warning only makes a crash imminent situation worse if a driver does not know that the system is on board.

The subjective assessments of the participants fit well with the objec-

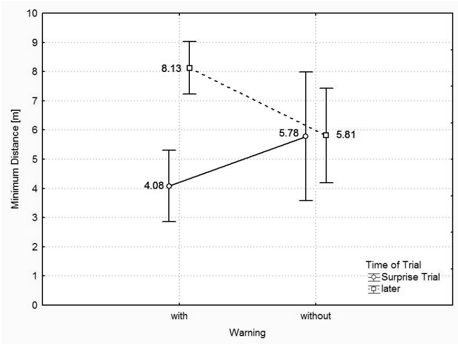


Figure 5.36: Minimum Distance, Surprise vs. later

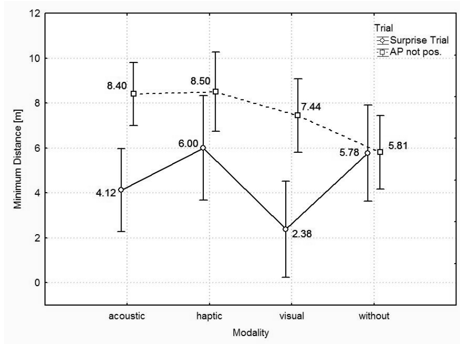


Figure 5.37: Minimum Distance split for modalities, Surprise vs. later

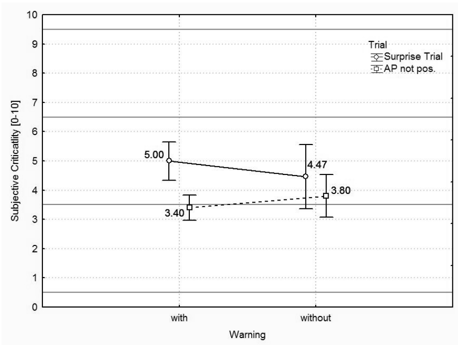


Figure 5.38: Subjective Criticality, Surprise vs. later

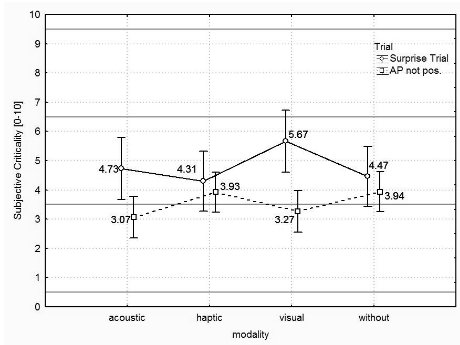


Figure 5.39: Subjective Criticality split for modality, Surprise vs. later

tive parameters. In Figures 5.38 and 5.39, the subjective criticality assessments of the situation are reported. The repeated measures ANOVA shows again a significant effect of the trial (df=1, F=21.52, $p<0.001$) and the interaction of trial and warning group (df=1, F=3.21, $p<0.05$). A descriptive look at the data split for modality shows similar results as the minimum distance or the the brake reaction time. The participants assess the surprise trial as "uncomfortable". With the visual warning, some participants even choose to assess it as "dangerous" which is comprehensible, since 33% of them had a crash with the lead vehicle. Similar results (with negative sign) can be observed with the subjective performance of the participants (cf. Figures 5.40 and 5.41. But it has to be emphasized that, for the performance assessment, only the factor Trial is significant (df=1, F=22.30, $p<0.001$). The assessment of the performance seems to be linked to the minimum distance. For the surprise trial the correlation is 0.7 and for the AP not possible it is 0.3. Both correlations are significant at $p<0.05$.

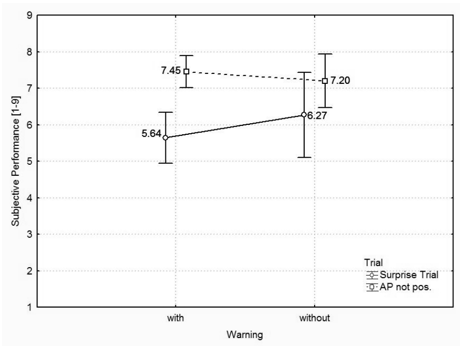


Figure 5.40: Subjective Performance, Surprise vs. later

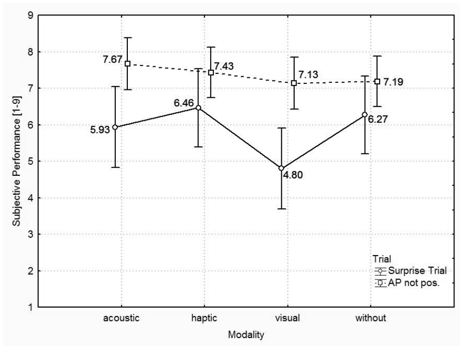


Figure 5.41: Subjective Performance split for modality, Surprise vs. later

5.3.3 Overreliance on Warnings

After pilot testing, apprehension arose. Drivers with warning might rely on the warnings too much. In particular, the idea was that drivers could delay their reactions to the threats in the AP *possible* situations or even wait for the warning to go off. To test this hypothesis, the AP *possible* situations of the Lead vehicle Braking and the Pedestrians crossing the street were included in the training with small changes. The changes were made to make recognition of the situation difficult for the participants. The behavior of the hazardous road user was not changed in order to make the situations as comparable as possible. In the training, the knowledge of all participants was the same and no participant received a warning. The order of the scenarios was the same for all participants.

1. Lead vehicle braking after using the turn signal

2. Pedestrian crossing the street without obstruction of sight

To test this hypothesis, repeated measures ANOVAs have been calculated. The independent factors are “Trial” and “Warning group”. Both factors have two levels. As in the other analysis, a factor for comparability is the velocity at which the BRT is taken. Because this analysis is done to check if drivers with the warning over rely on it, only the Accelerator Pedal release time and the BRT are examined.

Table 5.27: Objective parameters training vs. anticipation possible in experiment (Lead Vehicle Brakes)

Parameter		Warning	Trial	
			Training	AP pos.
Velocity at BRT	km/h	With	52.10	51.46
		Without	52.01	51.60
Acc. pedal release time	ms	With	-169	-952
		Without	-421	-771
Brake Reaction Time	ms	With	864	320
		Without	395	244

Lead Vehicle Brakes Scenes

The mean values for the objective measures of the Lead vehicle brakes scenarios are presented in Table 5.27. The descriptive data of the speed at the BRT shows slightly higher values in the training than in the main experiment. But no factor has a significant impact on the velocity. Therefore, the data can be analyzed without restrictions.
The Accelerator release time is different between the training trial and the trial in the main experiment. But this difference is not influenced by the warnings and therefore rejects the hypothesis that drivers react later with the warning. Both groups react earlier in the main experiment. The BRT is significant for the factor "Trial", which is irrelevant because, as for the Accelerator pedal release time, the second time the participants react earlier, not later. Interestingly, the warning group takes longer to step on the brake than the control group in the training (this interaction is only a tendency with p-value=0.12). Both groups did not get a warning in the training. But, although the warning group tends to react slower, they do not in the main experiment. Therefore, the hypothesis has to be rejected for the braking scene.

Pedestrian Crossing Scenes

The mean values for the objective measures of the Pedestrian Crosses the Street scenarios are presented in Table 5.28. In the comparable situations for the pedestrian who crosses the street, the initial velocity differs for the warning type in 1 km/h (df=1, F=7.32, $p<0.01$). As there is no difference between the trials, they can be compared for each group. As in the LV brakes scenarios, the Accelerator pedal release is initiated earlier in the AP *possible* scene in the main experiment. The reaction to the pedestrian is quickened

Table 5.28: Objective parameters training vs. anticipation possible in experiment (Pedestrian X-ing)

Parameter		Warning	Trial Training	AP pos.
Velocity at BRT	km/h	With	52.55	52.33
		Without	53.49	53.40
Acc. pedal release time	ms	With	-1670	-2100
		Without	-1753	-2179
Brake Reaction Time	ms	With	-1053	-1211
		Without	-1131	-1042

by about 400 ms. Again, this does not lead to a later BRT with a warning later in the experiment (cf. 5.28). The early accelerator pedal release in the AP *possible* scene leads to a higher variance in the BRT. This might be explained by the fact that the participants recognized the pedestrian and waited for the braking differently according to their driving style. Therefore, the hypothesis that the drivers wait for the warning until they react can be rejected for the pedestrian crossing scenes, as well.

5.3.4 Validation of Study One

To make the results of Study Two comparable to Study One, a small replication of this Study was made with the setup of Study Two (cf. Section 5.2). As there was the assumption that the modality in the main part of the study could have an impact on the results in the validation experiment, the parameters were tested with a repeated measure ANOVA with the factors Modality and Time and, as a categorical factor, the "Modality in the Main Part". The main focus lay on the BRT and the order of the modalities. The mean values of the BRT are laid out in Table 5.29. The order is the same as it was in Study One, but the BRTs are generally higher and the differences are smaller. The ANOVA revealed that only the Modality of the signal (df=2, F=6.48, $p<0.01$) and the interaction of Modality $\times$ Modality in Main Part (df=6, F=2.6, $p<0.05$) are significant. A post-hoc Tukey test for the main factor Modality shows that the visual warning leads to longer RT than the other. The results split for the interaction are shown in Figure 5.42. Unexpectedly, the group without warnings from the main part is the fastest regarding the descriptive data. The results of the post-hoc test show no general difference for this group. But the post-hoc test shows that the haptic seat group is, with the visual warning, slower than the without group with any warning. Furthermore, the Acoustic group is slower with the Seat

Table 5.29: Measures for validation of Studie I

		Modality		
Parameter		Visual	Seat	Tone
Brake Reaction Time	ms	905	864	844
Perceived Urgency		4.32	5.58	5.48
Appropriatness as FCW		3.48	5.36	5.46

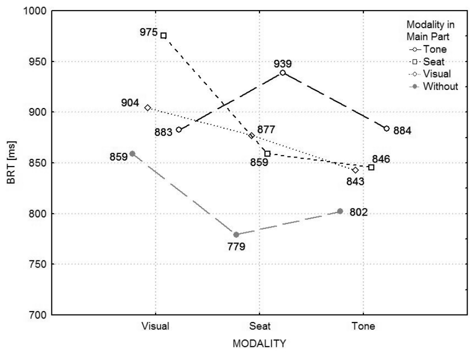
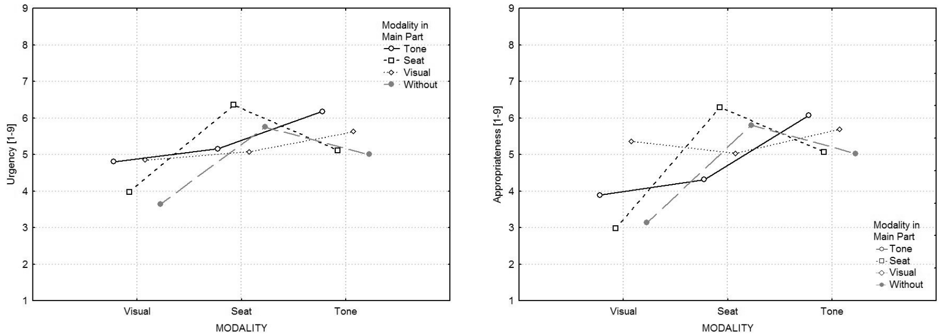


Figure 5.42: Brake Reaction Time (Modality × Modality in Main part)

warning than the without group is with the same warning.

Another important variable is the perceived Urgency (cf. Table 5.29). In the Original experiment, the Tone warning elicits the highest Urgency ratings. Seat and visual warning had similar but lower ratings. In the replication, Tone and Seat are similar and the visual warning has lower ratings. It seems that the new / different seat vibration has an effect on the perception of Urgency and is somewhat stronger than the one in Study one. The ANOVA's result is a significant effect of Modality and the interaction of warning Modality (df=2, F=16.18, $p<0.001$) and Modality in the Main Part (df=6, F=3.42, $p<0.01$; see also Figure 5.43a). According to the post-hoc test, the ratings for visual warning is lower than the other two. The significance of the interaction is based on the facts that the without and haptic seat group rate the urgency of the visual warning very low and the seat group rates the seat high, whereas the acoustic group rates the Tone warning high.

In the answers to the question of appropriateness, the dependencies on the groups become even more obvious. Looking only at the modalities, as in Table 5.29, the result is similar to the Urgency. But Figure 5.43b depicts that the best rating for each warning modality is given by the group that had the particular warning in the main part. This interaction becomes significant (df=6, F=5.5, $p<0.001$) and the post-hoc test shows that, in particular, the visual warning is rated positively by the visual group and the seat is rated positively by the seat group.



(a) Perceived Urgency **(b)** Appropriateness as FCW

Figure 5.43: Subjective Measures split by Modality in validation study × Modality in main part

5.3.5 Summary of Results

It can be stated for the main part of the study that, regardless of the threat type, the anticipation level makes a difference on most dependent variables. For example, the participants reacted earlier and more softly in situations where anticipation was possible. The reactions were the latest and most intense when the participants' anticipation was misled by a wrong stimulus. The difference between the AP levels *not possible* and *wrong* was small with warnings and larger without warnings. It seems that, with the help of the warnings, the participants could compensate the delay caused by the wrong anticipation. A further central result is that the participants' judgment of their performance correlates significantly with the minimum TTC experienced during the particular event regardless of the independent factors.

If the warnings had an effect on the dependent variables, a descriptive analysis of the effect of warning modalities has taken place. The most drastic result in matters of effects of modalities has been found in the trials of the surprise event. The mean values of BRT for all surprise events with warnings were slower than without a warning. But the visual warning is the only modality that is significantly slower than the control group. The difference of BRT mean values between these groups is 246 ms. Results from the same event later in the experiment show that the participants with warnings learn to benefit from the warnings, whereas the control group's BRT does not alter during the experiment. The acoustic warning group showed a tendency to be faster than the control group in the later event.
Another important observation is that the different threat types (car brakes vs. pedestrian vs. car takes ROW) lead to different behavior. In the Lead

vehicle brakes situations, besides the AP level, the warning modalities had effects. The modalities produced an order of the brake reaction time in the *not possible* and *wrong* levels. The order for BRT is as follows: Acoustic $<$ Haptic Seat $<$ Visual $<$ Without. A strong effect of the warnings is also given for the parameters first local maximum of brake pedal position, minimum TTC, and minimum distance. Quite striking is that the different AP levels have a minor effect on the warning group and a bigger one on the control group. In the Pedestrian Crossing scenarios, the Accelerator pedal release time and the BRT differ a lot because of the AP level, but not because of the Warning. The minimum TTC and minimum distance do not have a significant effect on the Modalities but show the same tendency as in the Lead Vehicle Brakes situation (but the Haptic Seat can not be counted due to wrong starting conditions). Again, the correlation of minimum TTC and subjective Performance is significant.
Regarding the influence of the warning, the third threat type, Car takes the Right of Way, is different than the aforementioned. The warnings/modalities do not impact the reactions of the participants at all. The AP levels lead to similar effects than in the other scenarios. In general, the reactions of the participants are very early. They are so early that, in the *not possible* and *wrong* condition, the BRT resembles the GRT in the other threat type scenarios. The subjective Criticality of the situation compared to the other two threats is higher in total. And even the AP *possible* situation's criticality is rated as "uncomfortable" (4.85 on the scale). The correlation of minimum TTC and subjective performance is, for this threat type, not significant.
The check on overreliance on the warnings in AP possible scenes did not reveal this kind of behavior.
The replication of the first study showed that the change of setup regarding the hardware and tasks of the participants changed the RTs and the subjective assessments. The Haptic Seat and the Acoustic Warning are much closer than in the first study regarding BRT and subjective assessment. Still, the visual warnings lead to slower reactions and worse judgments. But the participants were largely influenced by the warning they experienced earlier in the main part. The participants with the haptic and acoustic warnings in the first part assess the warning they have experience with better than the other warnings. Generally, it could be shown that the control group has the shortest reaction times in the simple reaction time experiment.

5.4 Discussion

This experiment studied attentive drivers. It investigated the effects of Forward Collision Warnings for three different levels of threat anticipation and three different threat types on behavioral data (specifically brake responses) and subjective assessment of the situation. Both types of measurement (objective and subjective) differed significantly for the anticipation level factor in all threat types. The participants always reacted earlier and judged the situation as less critical in the anticipation *possible* scenarios than in the *not possible* or the *wrong* scenarios. This shows the AP level scenario design affected the driver's behavior and situation assessment. If the major difference in results was due to the correctness of the driver's anticipation process associated with the situational awareness concept, the results offer a possible explanation for the high number of crashes that are reported in crash databases with attentive drivers. The wrong anticipation led the drivers to misprioritize their attention. If drivers correctly anticipate threats, collision imminent situations seldom occur. If a driver cannot anticipate a threat, especially when the situation is ambiguous, avoidance reactions are performed later. This might sound like a trivial statement, but this study suggests that, for example, a turn signal from the lead vehicle, or the introduction of a second car, can make a crash more or less likely. Drivers may not pay attention to the more relevant source of danger because it is not anticipated to be a potential threat. This provides a cause for the inattention category "misprioritised attention" (Regan et al., 2011) as presented in section 2.1.4 Attention. This is an additional explanation beyond the Looked-but-failed-to-see phenomenon (e.g., Brown, 2005), that also explains crashes with alert drivers.

The accelerator pedal release times and the brake reaction times in the Lead Vehicle brakes trials of this experiment are very comparable to the measures from the first experiment, if the trials without possible anticipation are regarded. Mean BRT of the acoustic warning in Experiment 1 was 666ms and 689ms in the comparable scenario of Experiment 2 (LV brakes, AP not possible). For both hazards with crossing road users,the accelerator release time especially occurs much earlier and demonstrates the anticipative avoidance behavior.

This study suggests that FCWS - especially warnings of audible or haptic modality - can help attentive drivers. This statement is correct in particular when the situation is ambiguous. There was little positive influence on objective data of the warnings in the pedestrian crossing scenes and it was not measurable in the right of way scenarios. This could be due to the visual appearance of the introduced threat. The cars and pedestrians in the situations without the possibility to anticipate the threat emerge suddenly from behind a corner of a house or the transporter. It may be that this type of stimulus triggers a lower level attentional process, as opposed to an anticipatory process associated with situational awareness. In the other scenario types, such a lower level process may not be triggered. This could be explained as such that in the brake scenario the lead vehicle is part of the scene for a longer time and the participant must notice brake lights which were relatively small on the screen and were of course not illuminated as they had been displayed on a LCD screen.

Further experiments could be utilized to attempt to validate the hypothesis of the interaction of FCW effectiveness and threats eliciting a lower level attention process. One possible test setup could include the usage of the "lead vehicle brakes" scenario while modifying the size and luminance of the brake lights to manipulate the saliency of the attentional cue.

Chapter 6

Discussion

This thesis has deliberately concentrated on attentive drivers[1] in imminent crash situations. The focus of this work has been the exploration of the reasons for crashes involving attentive drivers and the possible advantages of Forward Collision Warnings (FCW) for them. To achieve high transferability of the results and to enable a high reproducibility of experimental tasks, the use of a driving simulator was introduced. Typically, simulator studies in the domain of FCW and collision avoidance use simple driving scenarios and focus on rear-end crashes only. The studies often investigate inattentive drivers or use techniques like disabling the brake lights of the hazardous lead vehicle to focus on the support of the warning. These methods reduce the transferability of the results to real traffic scenarios.
The settings of the driving task in this thesis reflected typical crash scenarios in urban areas with a minimum of instructions to the driver. A variety of hazards has been tested: rear-end collision situations, cars that take the right of way, and pedestrians who cross the street. With this variety of test scenarios it was possible to identify different driver reactions, and the varying need for FCW in different situations could be investigated. The only study dedicated to forward collisions which has so far shown an influence of the anticipation of drivers on crash avoidance works with a lack of anticipation (Muhrer & Vollrath, 2010). The present thesis also showed that (misled) anticipation could make the situation worse. Additionally, the influence of different warning modalities was tested.

The driver's anticipation or expectation is essential for safe driving. The research clearly shows the relevance of these abilities. The participants

[1]Drivers that are actively involved in the driving task, have their hands on the steering wheel and look to the forward road scene or check mirrors / instruments are thought to be attentive drivers.

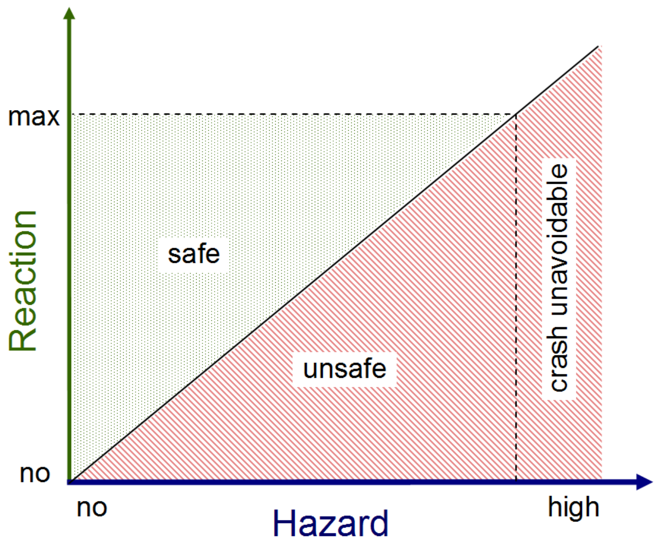


Figure 6.1: Intensity of Hazard and Reaction

extracted relevant cues and adjusted their behavior in a way that demonstrated their situational awareness, including a “projection of future state” which resulted in anticipative behavior. Considering the proposed threefold model of the Signal Detection Theory (see page 67), reactions without anticipation would not be expected until the hazard/danger is present. This is resembled in the top layer of the cube or combinations 1 to 4 in table 2.9. But as the context analysis of accelerator release and brake pedal actuation show, the participants react clearly before a hazard was present (combination 7 in the table). In the nomenclature of the threefold approach developed prior to conduction of the experiments, this would be an “independent, unnecessary precaution”. “Unnecessary” is clearly a false statement. After evaluating driver situation assessment and behavior in the different situations, it is clear the categories “Hazard” as well as the driver’s “Reaction” cannot be seen in a dichotomous way as proposed earlier. The threefold approach is still correct, but the SDT can be applied only to the system detecting a threat (a certain threshold) or the human detecting the warning. The reaction of the driver to the situation (danger) is adaptive and does not look for a certain threshold. Therefore this needs a renewed approach. This is visualized in Figure 6.1. The Hazard can increase on an interval scale (for example, measured in TTC). The reaction also increases on an interval scale (for example, measured in deceleration). With a certain Hazard intensity, a certain (minimum) Reaction intensity would avoid a mishap (e.g., crash). This is represented by the solid diagonal line. Every reaction that is more intense than this line is safe behavior, represented by the green dotted area. Weaker reactions are unsafe and lead to mishaps, represented by the shaded red area. But the

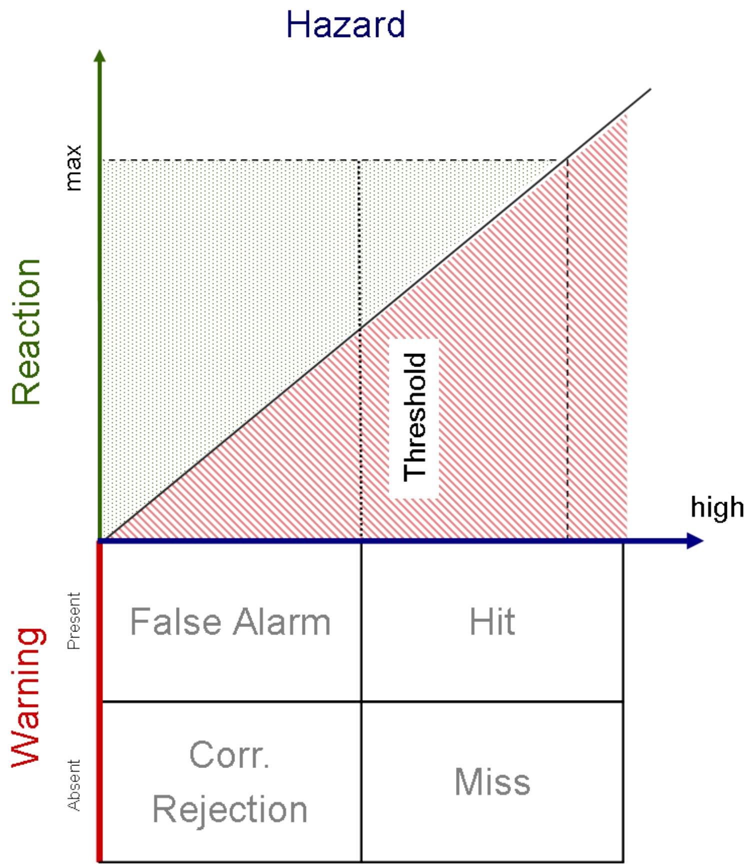


Figure 6.2: 3-fold approach of Hazard, Warning and Reaction

Reaction intensity is limited to a maximum. If the Hazard intensity exceeds the possible Reaction intensity, a mishap or crash is unavoidable. The design of the warning system has to provide a threshold for the warning below this maximum Hazard intensity that is possible to be handled by the driver's reaction. The detection of this threshold can be analyzed by the SDT. The reaction of the driver can be analyzed best in comparison to the intensity of the hazard. In the experimental situations when cues for possible hazards where given, most of the participants reacted early in an anticipative way. Hence, their reaction would result in a point left in the green area of the schematic diagram of Figure 6.1. The complete threefold approach is depicted in Figure 6.2. The system's threshold is introduced and hence the SDT for the warning is included.

Regarding direct measures of the second experiment, the anticipative behavior of the participants can be seen in the driver reaction times, but also in more strategic decisions. Hence, the anticipative behavior is reflected in

the maneuvering and the stabilization level of driving. The participants were instructed to drive at a speed of 50 km/h. In the car following scenarios, the distance between host and lead vehicle was determined by the simulator. A lot of drivers regulated their accepted risk by slowing down and subsequently making the time gap larger. It was also shown that attentive drivers can handle unexpected situations quite well when their attention is directed at the dangerous road user. If warnings then go off, they are perceived as useful, but – as the control group shows – are not needed in these cases. If a second road user is in competition for the attention of the driver, the performance can drop quickly. Following the ABC model or the MOSAIC model (see Section 2.1.2), the attention is allocated top-down to the elements of the situation which are most relevant for the planned actions. The drivers seem to plan and anticipate their actions primarily with the road user regarded as being the most critical one. This is a reasonable decision and will probably work for most situations, especially in combination with the ability of human perception to trigger a lower level attention process, when suddenly appearing, moving or changing stimuli are noticed.
Therefore, two cases have to be separated for attentive drivers: If the hazard appears suddenly, the bottom-up attention process allows a fast reaction. The anticipation and the top-down allocated attention do not constrain the fast reaction on that kind of threat. The reactions are different if the hazardous road user has been part of the situation before and no cues indicate that he will change his behavior. Then, no bottom-up process will compensate the wrong anticipation of the driver. The reaction times increase and crash imminent situations occur with a much higher probability. But, a FCW can improve behavior in such a situation. Whether with or without a warning system, if cues in a potentially critical situation are provided, anticipative behavior (e.g., slowing down) prevents the driver from being involved in a crash or a near-miss. Without the warnings, the described happens. In situations without a cue but with a warning, the minimum TTC is just a little lower than with the cues.

What does the warning change in the perception of the driver? Is it the warning itself? Does it have to be learned?

These questions can be approached because of the experimental design chosen. The participants experienced the situation of the suddenly braking lead vehicle (*anticipation not possible*) twice. The first of the two situations was a surprise event. This means it was the first critical situation in the experiment and the participant did not expect critical situations at all and the FCW systems was unbeknownst to the driver. The second event was sometime later, after the participant had experienced at least three more critical events. At the surprise event, the group with warnings was slower than the group without a warning. This was especially the case for the visual warning group. Reaction times stayed the same for the no warning group in the surprise event and in the event when they experienced the situation for the second time. The warning group improved their performance so much that their avoidance behavior was better than that of the no warning group. What are the implications of these results? What could explain the bad performance of the warnings in the surprise trial?

Forward Collision Warnings do not simply work of their own accord. They have to be learned.

As all warnings were designed to be intrusive, the probability is high that they will trigger a lower level attention process. The seat vibration, acoustic signal, and the visual display do not have anything to do with the current situation but, because of the bottom-up process, they are attended to and processed. This itself – in contrast to the suddenly emerging threats (pedestrian or crossing car) – does not direct the driver's attention to the hazardous area / object. The haptic and acoustic warnings might have elicited a visual search for the reason of the warning, whereas the visual warning ties the visual attention directly to itself and congruously blocks the visual search. In addition, a result from Study One was that the visual warnings led to the slowest reactions, although this was a simple reaction experiment, where the possible triggers were known to the participants. Hence, the high reaction times to visual warnings plus the distraction from the threat area could be an explanation for the eminently slow reactions in the surprise trial with the visual warning.

After the initial learning phase (which could be as short as one trial), the warnings facilitate the reactions in the situations without cues. What causes this change? The forward collision system itself calculates Time-to-collision. Hence it acts on a "projection of the future" because, if the driver will not intervene, a crash will happen in the calculated time. To calculate this TTC the current path of the host vehicle and lead vehicle are taken into account. As explained earlier, the approach for the system and a human is not so different. Assuming that the driver interprets the warning as what it is – the system's anticipation of a forward collision – it could enhance his situational awareness process. If the driver then learns over time to be able to rely on the system, it could directly affect his decision making process, as the perception of the warning equates to the anticipation of a certain "protection of future status". If so this means it changes the process model as invented in Chapter 3 on page 70. This change is depicted in Figure 6.3 with the additional arrow from the box "Perception of elements in Current Situation" to the "Decision". The proposal here is that a highly learned warning could substitute the whole situational awareness process. The perception of the warning stimulus would then be enough to lead to accepting the anticipation. If this would be the case, the driver could gain time by initiating avoidance

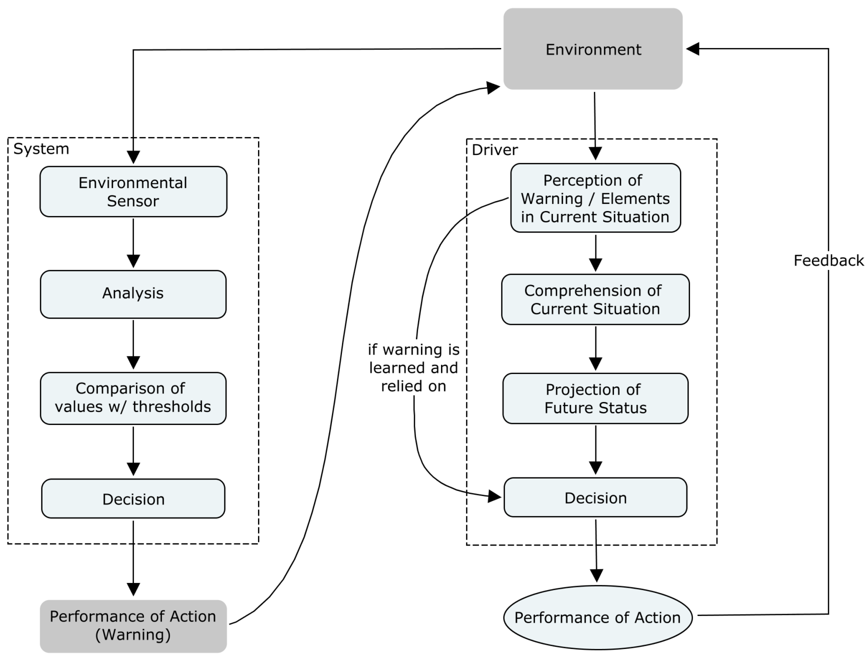


Figure 6.3: Process Model for Dynamic Warnings with a learned meanings

behavior faster. The adjustment of the behavior parameters (e.g., force, speed, etc.) to the situation in question could be performed online during the performance of the avoidance behavior. The learning theory behind this idea is simple. It is stimulus-response learning. In the second experiment, the participants could learn that the FCW is always presented in more or less imminent forward collision situations. In all situations, braking has been the right behavioral response. Under these assumptions, a learned Forward Collision Warning has three effects on the receiver / driver:

1. The anticipation of an imminent forward collision
2. Attention direction towards the potential collision obstacle
3. The initiation of an avoidance reaction (here to step on the brake)

This statement leads to further practical questions. Will a driver of a car equipped with a FCW system brake automatically when he perceives a warning? Would that lead to dangerous situations in false alarm situations? As this question has not been dealt with experimentally it has to be answered theoretically. The danger of a situation becoming hazardous because of a driver reacting to a false alarm appears to be low. To become hazardous, the initiated braking must be very intense. When talking of a learned response, the situations in the learning phase would also have to demand full braking reactions. But the frequency of full braking following a FCW in a system on the road is extremely low. Hence, the fear of a hazard because of the driver overreacting to a false alarm situation is not given. It is assumed that the driver will not slam on the brakes, because this would not be the learned response to the warning.

How much time does a FCW save? It seems to be highly dependent on the driver's experience with the system. As Lees and Lee (2007) showed, so-called "unnecessary" warnings fostered the driver's compliance and trust in the system, whereas "false alarms" dismissed compliance and trust. This result fits well to the ideas of a learned response and the substitution of anticipation. If the system is unreliable, no S-R connection can be built up and no clear situation anticipation will be developed.

A common approach of OEMs is to minimize false and unnecessary alarms. Within the OEM's view, a zero false alarm rate is still desirable. But, as this thesis shows, a 100% alarm hit rate only for situations that would have ended in a crash is not needed from an acceptance standpoint and is even counterproductive in regards to driver performance. As pointed out in Section 2.2.4, the estimation is a base rate of 173 crashes for every million lead vehicle stops, or a p of 0.000173 for freeway driving (Parasuraman et al., 1997). The driver has to learn the system's meaning and incorporate the warning into his situational awareness model. This would not be possible with a 100% alarm hit rate by definition.

A system timing or threshold that provides a warning in situations rated critical by the driver seems to be the most successful approach. The driver could gain life saving reaction time when he has learned the system in crash imminent situations, but would not be annoyed in critical situations. Even if a driver would not react with enough braking intensity in the first movement, the car would decelerate earlier and speed would be reduced. Additionally, the braking force could be adjusted by a technical system to mitigate the crash or even avoid it. In production systems, the annoyance factor is currently solved by the possibility of timing customization by the driver.

Another implication for production systems can be derived from the results of the first warning trials in both experiments. In both experiments, the first reactions to the visual warning were the slowest. On the one hand, this could originate in the fact that they are not omni-directional. As stated above, they have to be attended to actively. On the other hand, this seems to be the problem in the traffic scenario. The drivers were distracted by the visual stimulus away from the hazard. In FCW systems in production, the visual warning is always presented simultaneously with another modality.

Unfortunately, the simultaneous display of a warning tone, for example, will not diminish the distracting attributes of a visual warning. The deciding factor of a visual warning is its position. If the driver (different from the studies performed in this thesis) is inattentive, the visual warning can attract his attention and lead it in the direction of the threat. If this is the primary task of a visual warning, it should be very short. In the experiments performed, all warnings had a duration of 900ms. To deploy the positive effect of leading the attention, but not distracting the driver, a short visual warning could be added to another modality. It could accompany the onset of the other warning and serve as an attention grabber and leader. Conscious higher order processing is not needed. While an acoustic warning could continue, the visual warning should stop after, for example, two short flashes. The perfect place for this kind of visual warning would be the position or direction of the threat. Hence, some kind of display on the windshield would be a possible solution. An optimal solution would be a contact analog or virtual reality HUD that could mark the threat directly.
The results show that the warning design is essential for effectiveness of the first warning. The results also show that, for an attentive driver who knows the warning, the warning design does not play a big role. In combination with the model of externalized anticipation, the warning at that stage only has to be perceived by the driver. The combination of an intrusive haptic or acoustic warning plus a short, attention grabbing visual warning could be the perfect combination. It should minimize the negative effects of the visual warning for an attentive driver, but keep the attention directing positive effect for inattentive drivers.

To identify the possible threat of drivers braking hard in a false alarm condition, further experiments should be conducted. A possible experimental setup could include a “learning phase” with a 100% hit rate for crash imminent situations, which could be followed by a false alarm (without any lead vehicle) or an unnecessary alarm (with a lead vehicle braking lightly). This test would resemble a worst case scenario. As pointed out earlier, the hit rate in actual systems is not even close to 100%. The two different surrounding scenarios could show if the braking is just initiated or a complete reaction process is triggered by the warning. If the driver still checks the environment for proof, the reaction to the unnecessary alarm should be stronger than to the false alarm. On the other hand, the participant could experience only unnecessary alarms in the learning phase and then experience a real hazard to test the advantages of the warning similar to what Lees and Lee (2007) tested.

Conclusion

This thesis offered one explanation to why attentive drivers crash. It was hypothesized that the quality of the driver's threat anticipation has a major impact on the probability of the occurrence of a crash. The results show that, of the factors studied, the correctness of the driver's anticipation has the largest influence on driver brake reaction times and therefore on successful crash avoidance. A *learned* forward collision warning of any tested modality can compensate for the lack of threat anticipation, although visual warnings lead to poorer performance. Nevertheless, differences between driver reactions due to the warning modality seem to be of higher relevance for the phase where the warning is not known.
Hence, the results of this study suggest the use of a haptic or audible modality as a primary warning to the driver. The characteristic of visual warnings to draw the attention is both a blessing and a curse. It is suggested to use the visual warning component only for a short time to attract the driver's attention to the forward scene, but then end the display so no further distractions occur.

Car manufacturers should not suppress forward collision warnings just because the driver is looking out the windshield. If a driver reaches a critical situation represented by a low TTC or a high need for deceleration, he should always get a warning, unless he is braking or steering. The most important arguments for this are:

1. Looking at the street does not mean that the driver has the correct level of situational awareness.
2. The driver has to learn the meaning of the warning.
3. The driver will not be annoyed by such a warning.

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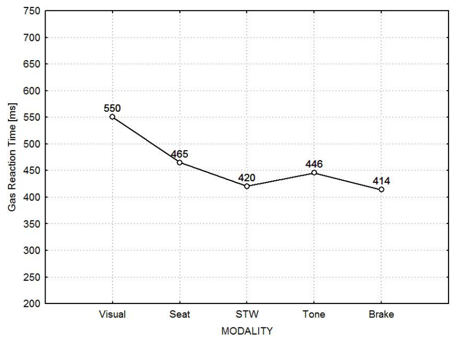
Appendix A

Additional Results

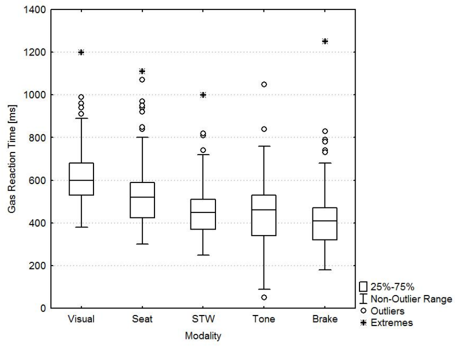
A.1 Study One

Table A.1: Repeated measures ANOVA for Gaspedal RT

	SS	df	MS	F	p
Modality	2179784	4	544946	24.73	0
Intensity	785350	1	785350	64	0
Time	258321	5	51664	3.21	0.011
Modality×Intensity	198400	4	49600	5.89	0
Modality×Time	872300	20	43615	4.05	0
Intensity×Time	105494	5	21099	1.74	0.135
Modality×Intensity×Time	621790	20	31090	3.28	0

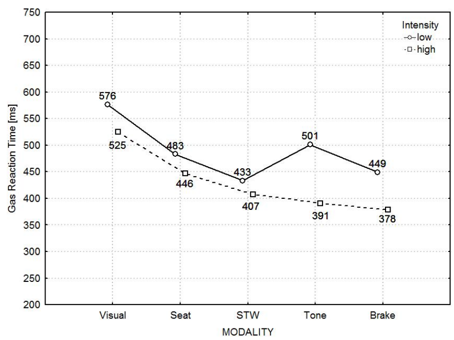


(a) Means

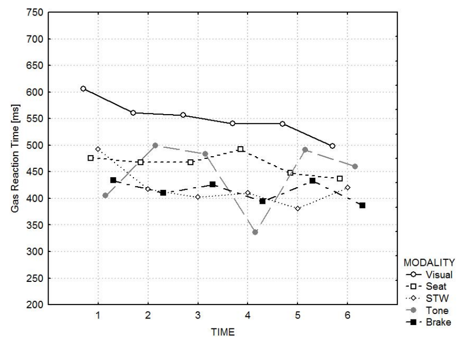


(b) Boxplot

Figure A.1: Gas Pedal reaction time split for Modality



(a) Means split for Modality and Intensity



(b) Means split for Modality and Time

Figure A.2: Gas pedal reation time

Appendix B

Questionaires

Würzburger Institut für Verkehrswissenschaften (Institute for Traffic Sciences)

In Zusammenarbeit mit: Interdisziplinäres Zentrum für Verkehrswissenschaften an der Universität Würzburg (Center for Traffic Sciences)

F602_01
Erklärung zum Datenschutz

Ich ______________________________
Name, Vorname

geboren am ______________

wohnhaft in ______________________________
Straße, Ort

wurde darüber informiert, dass während der Studie

____
Name der Untersuchung

Daten in folgender Form dokumentiert werden (**unzutreffendes bitte streichen!**):

- Demographische Daten
- Fragebogendaten
- Simulatordaten (Fahrdaten und ggf. physiologische Daten)

Ich bin damit einverstanden, dass die im Rahmen dieser Studie an mir erhobenen Daten aufgezeichnet, gespeichert und die Ergebnisse in wissenschaftlichen Veröffentlichungen verwendet werden können. Eine Veröffentlichung erfolgt ausschließlich in anonymer Form. Es ist mir bekannt, dass ich diese Einwilligung verweigern kann, dass die Teilnahme an der Studie freiwillig ist und dass mir durch eine Nichtteilnahme keine Nachteile entstehen.

______________________ ______________________
(Ort, Datum - **vom Testfahrer einzutragen**) (Unterschrift des Testfahrers)

____
(Unterschrift des Testleiters)

WIVW GmbH / F602_01 / Erklärung zum Datenschutz / Author: SH / **Effective Date** 2008-08-24 / F602_01 v2.1 supersedes F602_01 v2.0
CONFIDENTIAL

Figure B.1: Privacy consent form. Used in Study 1 and 2

1. Wie dringlich war diese Warnung?

Gering			Mittel			Stark		
1	2	3	4	5	6	7	8	9

2. Wie ernsthaft war diese Warnung?

Gering			Mittel			Stark		
1	2	3	4	5	6	7	8	9

3. Wie sehr schreckte Sie diese Warnung auf?

zu wenig			angemessen			zu stark		
-4	-3	-2	-1	0	+1	+2	+3	+4

4. Wie sehr würde diese Warnung Sie stören, käme sie 1x pro Woche ohne tatsächliche Gefahr.

Wenig			Mittel			Stark		
1	2	3	4	5	6	7	8	9

5. Wie gut ist diese Warnung als Kollisionswarnung geeignet?

Wenig			Mittel			Stark		
1	2	3	4	5	6	7	8	9

VpID [ ] ModBed [ ] Datum [ ]

Alter:

Geschlecht: w m

Seit wann besitzen Sie Ihren Führerschein (Jahr)?

Wie viele Kilometer sind Sie ca. in den letzen 12 Monaten gefahren?

Haben Sie Erfahrung im Fahrsimulator? Ja Nein

Falls **Nein**, Erfahrung mit Computerspielen? Ja Nein
Falls **Ja**, Erfahrung mit Autospielen? Ja Nein

Eingewöhnungsfahrt

1. Wie anstrengend war die Fahrt?

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

2. Wie schwierig war die Fahraufgabe?

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

3. Wie sicher beherrschen Sie das Fahrzeug?

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

4. Wie hilfreich war diese Fahrt für die Fahrzeugbeherrschung?

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

5. Ist Ihnen schlecht geworden? ◯ **JA** ◯ **NEIN**

Wenn ja: Wann, warum & Anmerkungen bitte auf der Rückseite beschreiben. Danke.

6. Ausgehend von Ihrem momentanen Befinden: Wie gerne möchten Sie jetzt noch einmal Simulator fahren?

gar nicht	sehr ungern	ungern	mittel	gerne	sehr gerne

VpID [ ] ModBed [ ] Datum [ ]

Allgemeine Fragen:

7. Alles in allem, wie sehr haben Sie die Warnungen bei der Kollisionsvermeidung unterstützt?

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

8. Diese Art der Warnung ist als Kollisionswarnung verständlich.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

9. Die Warnungen haben mich von der Fahraufgabe abgelenkt.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

10. Die Warnungen haben mich gestört/genervt.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

11. Ich konnte während der Fahrt auf die Warnungen des Systems vertrauen.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

12. Aufgrund der Warnungen des Systems bin ich risikoreicher gefahren.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

13. Aufgrund der Warnungen des Systems bin ich sicherer gefahren.

gar nicht	sehr wenig	wenig	mittel	stark	sehr stark

14. Erinnern Sie sich an die Situation, in denen die Warnung Ihnen am meisten half? Bitte beschreiben Sie kurz das Besondere an der Situation:

____

____

____

15. Erinnern Sie sich an die Situation, in denen die Warnung am unnötigsten war? Bitte beschreiben Sie kurz das Besondere an der Situation:

____

____

____