Navigation in the Augmented Reality Head-up Display

Guidelines for the Development of AR HUD Navigation Concepts

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Dedicated to my friends and to my German and Italian family.

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Abstract

As traffic gets more and more complex, companies and researchers are developing cutting edge technologies that aim for making driving safer. Today, *head-up displays* (HUDs) make it possible to display driving-related information directly in the driver's primary *field of view* (FOV). A promising advancement of this technology is the implementation of *augmented reality* (AR) and thus, showing virtual information in a contact analogue way, directly superimposed on the real-world environment, aiming to enhance driver safety and comfort. However, there are still technical limitations to consider, such as a limited FOV or inaccurate positioning of the virtual content due to inaccurate sensory data.

In this dissertation, four empirical studies were conducted to create a navigation concept for *augmented reality head-up display* (AR HUD) that supports the driver in the best way possible. In the first study, two 3D projects for creating and comparing AR HUD concepts were developed. The exemplary use cases were *navigation*, *lane departure prevention* (LDP), and *collision prevention assist* (CPA). In addition, this concept development approach was compared to another popular design method which is based on the mapping of virtual objects onto real driving scenes. The results of this expert evaluation contain suggestions on how to improve the approach using a 3D tool and on how an ideal concept development process for AR HUD could look like.

For the following study, a pure contact analogue navigation concept for AR HUD was developed. The aims of this study were to find ways to reduce masking effects without impairing the displayed navigation information and collect expert knowledge concerning AR HUD concept development. In the subsequent study, a revised navigation concept was developed and compared to the first one. The results show that the participants prefer the revised version of the concept. Eventually, the improved concept was compared to a static HUD navigation to evaluate, how the new technology performs against an already existing one. All of these field studies were conducted with a prototype vehicle that contained a complete AR HUD testing environment. Based on the field studies, design guidelines for the use case navigation were summarised and described.

Zusammenfassung

Mit dem immer komplexer werdenden Verkehr sind Unternehmen wie Forscher bestrebt, neue Technologien zu entwickeln, welche das Fahren sicherer machen sollen. *Head-up Displays* (HUDs) bieten die Möglichkeit, relevante Informationen direkt im Sichtfeld des Fahrers (Field of View, FOV) anzuzeigen. Ein großer Vorteil dieser Technologie ist die Integration von *Augmented Reality* (AR). Damit können virtuelle Daten direkt in die reale Umgebung eingebunden werden, mit dem Ziel, Fahrsicherheit und -komfort zu erhöhen. Dabei sind jedoch weiterhin verschiedene Einschränkungen zu beachten, wie ein limitierter Anzeigebereich, oder ungünstige Platzierung der virtuellen Information aufgrund ungenauer Sensordaten.

In dieser Dissertation wurden vier empirische Studien durchgeführt, um ein Navigation-Konzept für *Augmented Reality Head-up Display* (AR HUD) zu entwickeln, das den Fahrer auf bestmögliche Weise unterstützt. Die erste umfasst Entwicklung und Evaluation zweier 3D Projekte zum Erstellen und Vergleichen von AR HUD Konzepten. Die exemplarischen Anwendungsfälle waren *Navigation*, *Lane Departure Prevention* (LDP) und *Collision Prevention Assist* (CPA). Zusätzlich wurde dieser Konzeptentwicklungsansatz einer weiteren verbreiteten Entwicklungsmethode gegenübergestellt, die auf dem Einbetten von virtuellen Objekten in Realfahrszenen basiert. Die Ergebnisse dieser Expertenevaluation beinhalten Vorschläge, wie man den Ansatz basierend auf 3D Projekten verbessern kann und wie ein idealer Konzeptentwicklungsprozess für AR HUD aussehen könnte.

Für die nächste Studie wurde ein komplett kontaktanaloges Navigationskonzept für AR HUD entwickelt. Das Ziel dieser Feldstudie war es, Wege zur Reduzierung der Maskierungseffekte zu finden, ohne die angezeigten Navigationsdaten zu beeinflussen. Dabei sollten auch Expertenmeinungen zur Entwicklung von AR HUD Konzepten gesammelt werden. Das nächste Experiment umfasst die Erstellung eines überarbeiteten AR HUD Konzepts und dessen Vergleich mit dem vorherigen. Die Ergebnisse zeigen, das die Teilnehmer das überarbeitete Konzept bevorzugen. Zuletzt erfolgte die Gegenüberstellung

des verbesserten Konzeptes zu einem statischen HUD, um zu untersuchen, wie die neue Technologie gegenüber einer bereits existierenden abschneidet. Sämtliche Feldstudien wurden mit einem Fahrzeugprototypen durchgeführt, der über eine vollständige AR HUD Testumgebung verfügt. Die beschriebenen und zusammengefassten Konzeptentwicklungs-Guidelines für den Anwendungsfall Navigation basieren auf diesen.

List of Abbreviations

ABS	Antilock Brake System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AR	Augmented Reality
AR HUD	Augmented Reality Head-up Display
ATT system	Advanced Transport Telematics System
AVS	Augmented Video System
BSM	Blind Spot Monitoring
CPA	Collision Prevention Assist
DALI	Driving Activity Load Index
DAS	Driver Assistance System
DLP	Digital Light Processing
ECG	Electrocardiogram
EDA	Electrodermal Activity
EEG	Electroencephalogram
ESC	Electronic Stability Control
ESoP	European Statements of Principles
FOV	Field of View
HAD	Highly Automated Driving
HCI	Human-Computer Interaction
HDD	Head-down Display
HMI	Human Machine Interface
HOV lane	High Occupancy Vehicle Lane
HUD	Head-up Display
ICA	Index of Cognitive Activity
ISO	International Organisation for Standardisation
LCD	Liquid Crystal Display
LDP	Lane Departure Prevention
LDT	Laser Display Technology Displays

MBUX	Mercedes-Benz User Experience
MTC	Mercedes-Benz Technology Centre
NASA-TLX	NASA Task Load Index
NHTSA	National Highway Traffic Safety Administration
Open GL	Open Graphics Library
PGU	Picture Generating Unit
TAM	Technology Acceptance Model
TICS	Transport Information and Control
UEQ	User Experience Questionnaire
VFD	Vacuum Fluorescent Display

Content

1 Introduction

Traffic gets more and more complex and thus, the requirements on drivers rise (Heiner Bubb, 2015b). For this reason, companies are working on cutting edge technologies and systems that aim to make driving safer. Today's modern vehicles are already equipped with a large number of *driver assistance systems* (DASs) to support the human in challenging and complex traffic situations (Bengler et al., 2014). *Head-up displays* (HUDs), which are integrated into many of today's motorcars, are one example of a current DAS technology. This technology assists the driver by displaying driving-related information, such as the current speed, traffic sign information, or navigation hints, in the primary *field of view* (FOV) (Gabbard, Fitch, & Kim, 2014). This is realised by projecting a virtual image onto the vehicle's windshield. When using a HUD, the need to avert the gaze from the road scene for gathering driving-related information is reduced and the driver does not have to shift the attention away from the traffic scene. Further, the accommodation, adaption, and eye movement effort of the driver's eyes are reduced and reaction times to unexpected traffic events decrease (Haeuslschmid, Pfleging, & Alt, 2016; Pfannmueller, Walter, & Bengler, 2015). Another positive effect that is related to the usage of HUDs is that eyes-off-the-road times get reduced. This is especially important since two seconds with a driver's eyes away from the street can cause serious accidents as humans do not react and respond to the surrounding world (National Highway Traffic Safety Administration (NHTSA), 2013; Zwahlen, Adams, & DeBals, 1988).

The integration of *augmented reality* (AR) can be seen as the next step in the development process of HUDs (Azuma, 1997). This advancement makes it possible to combine virtual and real information in the human's direct line of sight by projecting virtual content onto the vehicle's windshield (cf. Figure 1). The virtual information is shown to the driver in a contact analogue way, which means that the information is directly connected to the real environment. This can lead to the reduction of divided attention while driving. Moreover, the driver's attention can be guided to essential events or objects, e.g. landmarks or hazards (Gabbard et al., 2014). This technology is called *augmented reality head-up display* (AR HUD) and was first realised by Bubb (1975).

Figure 1: The combination of static and contact analogue information in the driver's primary line of sight (Continental AG, 2019).

1.1 Motivation and Objective of this Work

Until the AR HUD technology can be integrated into a series vehicle, there are still challenges to master. One of them is the correct superimposition of virtual content onto the real-world environment which can be problematic due to inaccurate road map or sensor data as well as problems with determining the absolute position and orientation of the vehicle (cf. Rabe, 2018). Further reasons for displacement of the AR content can be the tracking of the driver's head posture, the sitting position, and pitch and yaw movements of the motorcar. Moreover, uneven road surfaces can lead to vibrations, which disturb the positioning and association of contact analogue AR elements to their real-world counterparts. Another limitation is that visual information can only be shown on a small part of the windshield due to package limitations in the car. Additionally, superimposing virtual content onto the road scene and showing it in the driver's direct line of sight can lead to driver distraction. Also, parts of the traffic scene can be masked when showing too much visual information in the AR HUD. This can result in obscuring the driver's view of other road users or potential hazards (cf. Gabbard et al., 2014). Those limitations and challenges will remain in the foreseeable future, which means that developers and designers have to take them into account while creating AR HUD concepts that support drivers with the requirements of the primary driving task.

To date, many researchers in the field of automotive AR focus on the use case navigation while having shown the advantages of optical see-through systems over conventional map-based wayfinding solutions (e.g. Doshi, Cheng, & Trivedi, 2009; Kim & Dey, 2009). Furthermore, different design ideas for AR HUD navigation concepts have been investigated and first recommendations on how to design such concepts have been given. However, the amount of research papers that touch upon the investigation of navigation concepts is rather small. Also, most of those experiments have been conducted in a driving simulator with the AR elements directly integrated into the virtual driving scene. Hence, no real sensor data and hardware was used and no influences of environmental conditions were considered either. However, it would be important to take these things into account to get results that come from realistic research conditions and thus, are more valuable for AR HUD concept developers. The primary purpose of this work is to fill this gap and to give design recommendations for the use case navigation based on experiments that have been conducted in real traffic while using a prototype car with a real AR HUD setup.

1.2 Structure of this Work

In Chapter 2, fundamental information regarding visual perception is given and terms from the field of information processing are described. In Chapter 3, basic information concerning the components of the driving task together with an explanation of the term *advanced driver assistance systems* (ADAS) is given. Furthermore, the components of the navigation task are described and examples for current navigation systems in series vehicles are given. Chapter 4 contains detailed information about AR HUDs, whereby a comparison of *head-down displays* (HDDs) and HUDs is given as well. Next, the term AR is explained and technical functionality as well as different AR HUD technologies are described.

Finally, the benefits and limitations of an AR HUD are listed. As this work addresses the development process and design of AR HUD concepts, related design laws and guidelines are described in Chapter 5. Chapter 6 contains the development of two projects for the 3D modelling software *Cinema 4D* based on typical requirements of AR HUD concept developers. The aim is to provide a prototype for a virtual concept development environment for AR HUD. Furthermore, this approach is compared to an method based on virtual elements integrated in real driving scenes with empirical methods, such as self-designed questionnaires based on Likert scales and open questions. Finally, an ideal concept development process for AR HUD is suggested. Chapter 7 describes three field studies conducted in real traffic with a full AR HUD setup. The chosen experimental setup requires a great effort but highly increases the ecological validity compared to a study conducted in the laboratory. The aim was to develop a navigation concept for AR HUD and at the same time, provide guidelines for concept designers. Various empirical methods were used in the field studies, such as standardised questionnaires to assess user experience, system trust, and mental workload of the subjects. Self-designed questionnaires were used to evaluate particular concept design aspects. Furthermore, a think-aloud method and additional open interview questions were used and evaluated with a qualitative content analysis. Driving performance was measures by tracking navigation errors. In Chapter 8, the most important contributions of this work are summarised and discussed. Finally, Chapter 9 contains trends and future research topics in the field of AR HUDs in the automotive context.

1.3 Research Objectives and Questions

In the following, the studies that have been conducted in this work are listed together with the corresponding research questions:

Expert Evaluation: ***Development of two 3D projects for rapid prototyping of AR HUD concepts and suggestion of an AR HUD concept development process based on an expert evaluation.***

- **EE 1**: How could a 3D tool used for AR HUD concept prototyping and development look like?
- **EE 2**: Is the usage of 3D projects for rapid-prototyping a meaningful extension in the concept development process for AR HUD?
- **EE 3**: For which tasks do concept developers prefer the usage of 3D projects and for which tasks the usage of virtual elements integrated in real driving scenes is preferred?
- **EE 4**: How can a 3D project for AR HUD concept prototyping and development be further improved?
- **EE 5**: How could a meaningful AR HUD concept development process look like and which tools could be part of it?

Field Study 1: ***A Study to Collect Expert Knowledge for the Design of AR HUD Navigation Concepts.***

- **FS 1.1**: Can the application of the *Gestalt laws of perceptual organisation* help to design a navigation concept for AR HUD that covers less of the real environment while the comprehensibility stays the same?
- **FS 1.2**: How can designers create future navigation concepts for AR HUD that support the driver despite today's technical limitations?

Field Study 2: ***Further development of the AR HUD navigation concept.***

- **FS 2.1**: How do drivers assess the improved concept in contrast to the *solid fishbone concept*?
- **FS 2.2**: Does the more dominant animation of the improved concept distract the driver?
- **FS 2.3**: How can both navigation variants be further improved?

Field Study 3: ***Proof-of-concept***

- **FS 3.1**: How do drivers assess the AR HUD navigation concept in contrast to the conventional HUD navigation concept?
- **FS 3.2**: Do participants see an added value in the contact analogue concept despite current technical limitations?
- **FS 3.3**: How can both navigation variants be further improved?

Cross-Study:

- **CS 1**: How could a navigation concept for AR HUD look like, which supports the driver in the best way possible while considering today's technical limitations?
- **CS 2**: What are meaningful guidelines for the development of AR HUD navigation concepts?

2 Visual Perception and Information Processing

Drivers process a high number of traffic information with the visual sensory channel. According to research (e.g. Bergmeier, 2009; Schweigert, 2003), up to 90 per cent of the resources of the visual sensory channel are used during driving. To get a basic understanding of the components and functionality of this sensory channel, the anatomy of the human eye, the visual ability of depth perception, and the concept of visual attention are described in this chapter. Furthermore, related and driving-relevant topics like mental workload and driver distraction are explained.

2.1 The Human Eye

Most of the information relevant for the driving task consists of visual stimuli that are perceived with the human eye. In this section, a short description of structure and functionality of this sensory organ are given.

The eye is a complex sensory system and at the same time, the most sensitive organ that human beings have. It consists of an optical system that can capture, bundle, and redirect rays of light in a way that they optimally hit the photosensitive apparatus, called retina (Schandry, 2006, p. 242). A schematic drawing is illustrated in Figure 2.

The anterior part of the eye comprises of pupil, iris, cornea, and crystalline lens. The pupil, which is adjusted by the surrounding iris, is a diaphragm that regulates the amount of light entering the eye. Electromagnetic radiation with a wavelength between 380 and 780 nanometres can be seen as the light that humans are able to perceive. Within the visible spectrum, different wavelengths are perceived as different colours. The convex transparent cornea is the major refractive element of the eye, covering pupil, and iris. Together with the crystalline lens, the cornea formats the optical image on the retina, which contains the receptors required for vision. These visual receptors, called taps and rods, contain light-sensitive substances that produce electric signals that leave the eye via the optic nerve and will be forwarded to the human brain (Goldstein, 2015). The crystalline lens is fixed by ligaments, also called zonules, which are attached to the ciliary muscle. Actions of the ciliary muscle cause the zonular fibres to tighten or relax and thus, the accommodation of the eye can be realised. This function allows the human to bring objects in different distances into sharp focus. This ability decreases with age because the crystalline lens stiffens and eventually, the eye becomes *presbyopic* (Irsch & Guyton, 2009).

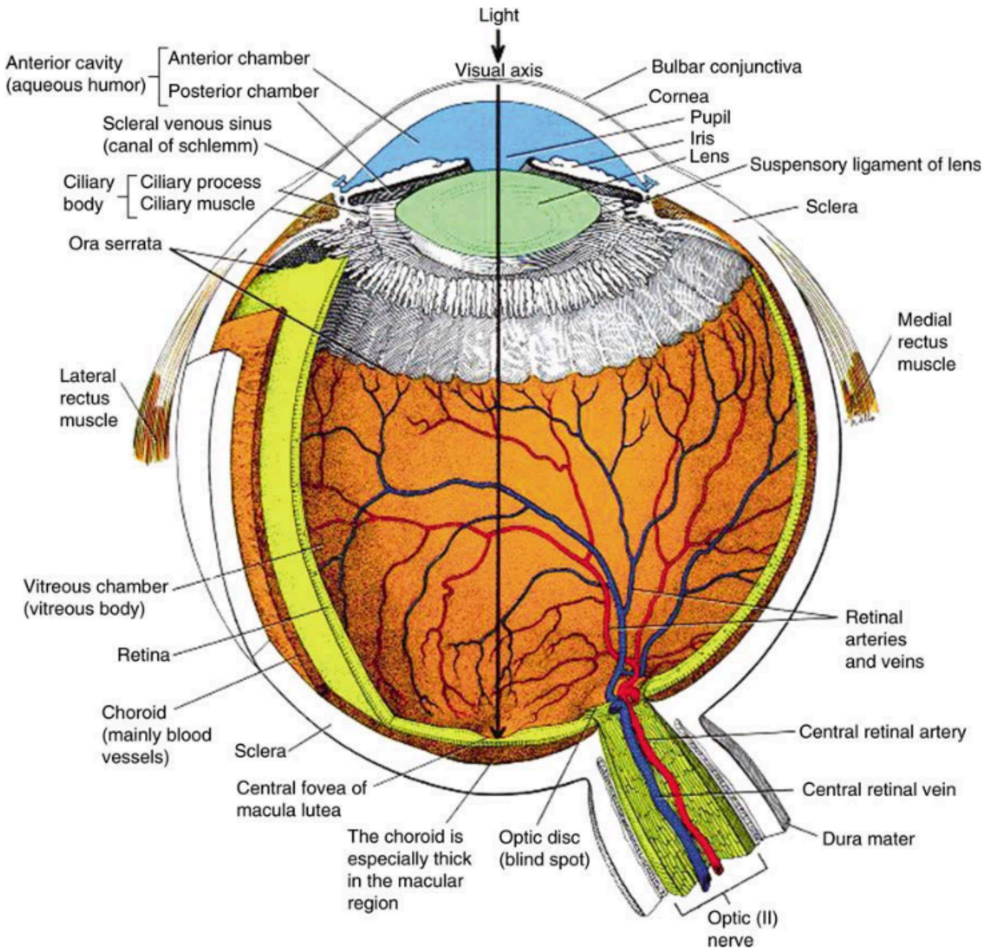


Figure 2: A schematic drawing of the human eye (Irsch & Guyton, 2009).

In case of an optical see-through display, developers have to face colour perception challenges associated with the fact that the driver's view is influenced by an interaction of real-world light and artificial light generated by the HUD. Studies have shown that this combination of different light types often leads to problems concerning the visibility and readability of the virtual AR graphics. In the automotive context, the colour blending problem is especially challenging as lightning conditions can vary greatly from bright daylight to darkness at night.

Another challenge is the alternating visual complexity of real-world backgrounds that can change from highly dynamic city environments to static rural scenes (Gabbard et al., 2014).

2.2 Depth Perception

Depth perception or judgement is essential in the automotive context, e.g. when searching for the right point to turn off or in heavy traffic situations with a lot of other participants. Information on spatial depth is not directly integrated into the retinal image due to being only two-dimensional. Hence, the visual system has to decode this information first with the help of depth cues that can be divided into three groups: The *oculomotor*, *monocular*, and *binocular depth cues*.

The *oculomotor cues* are based on feeling the tension in the eye's muscles and on sensing the position of our eyes. These feelings are caused by convergence and accommodation, which signal when an object is very close to the observer.

The *monocular cues* give depth information when observing a scene with one eye (Goldstein, 2009). The application of these cues helps to get a plausible integration of virtual content in the real-world environment. The depth cue of *occlusion* appears when one object covers or partially covers another one. The hidden one is perceived as further away from the viewer. Thus, only information concerning the relative distance is indicated. The cue of *relative height* comprises the phenomenon that humans perceive objects that are located below the horizon and higher in the FOV as being further away. In case of elements being above the horizon, a lower position in the FOV significates a greater distance to the observer. When two objects have the same size, the closer one will be perceived as being larger than the more distant one, according to the cue of *relative size*. This cue is based on the observer's knowledge of physical dimensions. According to the cue of *perspective convergence*, parallel lines are being perceived as converging when their distance to the observer increases. The cue of *familiar size* describes the fact that humans can be influenced by their prior knowledge concerning the sizes of objects to determine their distances. According to the cue of *atmospheric perspective*, elements further away from the viewer appear blurred and often have a blue tint while the closer objects are sharp. The explanation for this phenomenon is that observers have to look through a larger amount of air and particles (drops of water, air pollution, and dust) when objects are located in greater distances. The depth cue *texture gradient* describes that objects that are equally allocated in a scene, seem to be closer together with increasing distance. Another source of depth information is the cue called *shadows*. Shadows that are connected to single elements can give additional information concerning the objects' locations. Further, shadows point out the three-dimensionality of elements. In case of moving, two other monocular cues occur: The cue *motion parallax* appears e.g., when closer objects pass by in a fast way while the ones in the greater distance move slowly, as one looks out of a vehicle's side window. The cue of *deletion and accretion* describes the phenomenon that some objects become covered and some objects become uncovered while moving sideways. This cue is connected to both *occlusion* and *motion parallax* and is highly suitable for determining the differences in the distances of two surfaces (Kaplan, 1969).

In addition to the depth cues mentioned above, there is the *binocular disparity* that depends on both eyes. The source for this cue is the slight difference between the images received by the eyes, which are 6.5 cm apart in case of adults (Gazzaniga, Heatherton, & Halpern, 2010). With these two pictures, the human is able to determine the distance of objects by comparing their position in both images.

2.3 Visual Attention

The term *visual attention* describes a variety of cognitive processes that are responsible for filtering out irrelevant visual information and for selecting relevant visual stimuli. This ability is essential when driving a motorcar as otherwise the amount of visual information would overextend the limited mental resources of the human. Furthermore, developers and designers have to make sure to guide the driver's attention towards driving-related content, at best towards the primary driving task. Attention can be seen as a flexible construct that can operate on single features of an element, regions, or entire object (McMains & Kastner, 2009).

In the field of cognitive psychology, one can find at least two models that explain how visual attention works. The model which was mentioned in literature first is called *spotlight model*, whereby the term *spotlight* was influenced by James (1890), who stated that attention consists of the elements *focus*, *fringe*, and *margin*. The *focus* can be seen as the location to which the human's visual attention is directed as well as an area that selects information from a visual scene with a high-resolution. The *fringe* of attention surrounds the focus that extracts information which a lower resolution, i.e. in a cruder form. Eventually, the *fringe* extends out to a certain point while the cut-off is named *margin*. The second model was introduced by Eriksen & James (1986) and is known as the *zoom-lens model.* This concept contains all features of the *spotlight model* with the additional property of adapting size in relation to the human's current needs and intentions. This zoom-lens can be represented as an inverse trade-off between the efficiency of processing information and the size of the focus. As the resources of attention are believed to be fixed, it follows that the smaller the focus is, the faster the processing of visual information and the reaction to certain stimuli will be and vice versa (Castiello & Umiltá, 1990).

Further, attention can be directed towards an object or a location, either overtly or covertly. When deploying *overt attention,* the human selectively directs the gaze towards a specific item and can be recognised in the form of eye movements (Carrasco, 2011; Posner, 1980). On the other hand, when noticing an area in the peripheral field of vision without actually moving the eyes towards it, one speaks of *covert attention.* This kind of attention can be addressed to more than one element at the same time and thus, helps humans to observe the real-world environment. *Covert attention* is deployed in many everyday situations routinely and leads our gaze to areas where interesting or salient information can be found (Carrasco, 2011; C. W. Eriksen & Colegate, 1971; Posner, 1980). All forms of attention appear in everyday life while interacting dynamically (McMains & Kastner, 2009).

In contrast to Eriksen & Yeh (1985), more recent studies show that humans can divide their attention towards at least two areas or objects (Bichot, Cave, &

Pashler, 1999; Castiello & Umiltá, 1992; Cave, Bush, & Taylor, 2010; Jans, Peters, & De Weerd, 2010) and that attentional processes can be either serial or parallel (Julesz, 1991; Treisman, 1993). In contrast to *selective attention*, which describes the process of focusing the human's mental resources on single parts of the total current input (Kahneman, 1973, p. 2), the term *divided attention* aims at the optimal distribution of available resources over current information. This happens by rapidly shifting or splitting the attentional focus when processing all of the current input is not possible (Parasuraman, 1998). The human's attention can be allocated between attributes of single or various objects, various locations, and stimuli in one or more sensory modalities (Braun, 1998).

The phenomena *inattentional blindness* and *change blindness* show that attention is necessary to notice certain stimuli or information. The term *inattentional blindness*, also known as *perceptual blindness*, was characterised by Mack & Rock (1998) and describes the inability of humans to perceive sensory stimuli they are not paying attention to (Binder, Hirokawa, & Windhorst, 2009). In a famous study, Simons & Chabris (1999) demonstrated *inattentional blindness*. The investigators asked participants to count the passes made by basketball players dressed in white. Next, they were asked whether they saw a gorilla walking through the scene, which the participants denied. The term *cognitive capture* or *cognitive tunnelling* describes a form of *inattentional blindness* in which the human is focused on a specific stimulus or thought while not paying attention to the rest of the environment or the main task. In the context of HUDs, this phenomenon describes the ineffective attentional switching from HUD content to the primary driving task. Consequences could be delayed responses to traffic events, missing external targets, and unequal switching times (longer to switch from HUD to external stimuli). In this case, the HUD slows the processing of external information by claiming the human's information processing resources (Gish & Staplin, 1995). *Change blindness* describes a phenomenon in which modifications of visual stimuli or scenes are not noticed by the observer, despite being clearly recognisable. This often happens in case of two different images with significant changes flickering on and off. A reason for this inability to recognise major differences could be the given limitations of human resources concerning attention (Rensink, Regan, & Clark, 1997).

Visual attention can be voluntarily directed towards elements of current interest or can be attracted by salient features while these two processes can interact as well. Humans typically pay attention to single objects, one after another. Selection and order are related to two types of attentional mechanisms:

Bottom-up mechanisms operate on raw sensory input, involuntarily and automatically shifting the human's attention to salient visual stimuli that might be important. Thus, these influences are not directly connected to a spatial location or direction and can be expected from people in general, unless they have a specific impairment, such as being colour blind. An example of this mechanism could be an object suddenly starting to move, which could reflect an approaching danger (Connor, Egeth, & Yantis, 2004; Tobii AB, 2019).

The second attentional mechanism is called *top-down,* which comprises the human's longer-term cognitive strategies, often involving considerations. This individuating process leads attention to objects or areas that are currently important for the observer, e.g. corresponding shapes when fearing a wild animal (Connor et al., 2004). In case of concept design for automotive displays, *bottom-up* mechanisms can be used to guide the user's attention in accordance with the *top-down* aims. However, *bottom-up* influences could interfere with the driver's intentions as well (C. Wickens & McCarley, 2007). Thus, developers and designers need to make sure to consider these effects while creating concepts for an AR HUD. When the driver's attention gets shifted away from the driving task, it is essential to distinguish between *averting* and *distraction*. *Averting* is the deliberate decision to pay attention to other events than the driving task. *Distraction* happens when additional events attract the human's attention without him or her willing or planning to do so (*bottom-up*) (Bengler et al., 2014).

2.4 Mental Workload

According to DIN EN ISO 6385 (2016), the concept of *workload* can be defined as the sum of requirements of a task or a combination of tasks to a single person. However, a broadly accepted definition of this term does not exist (Cain, 2007).

There are three categories that can be associated with workload: The amount of work to do, available time, and the psychological experience of the executing person (Lysaght, Hill, Dick, Plamondon, & Linton, 1989).

For this work, especially the mental workload (also known as cognitive workload) is relevant as the tasks related to driving require mainly mental and less physical resources (Schmidtke & Bubb, 1993). Mental workload includes different processes such as cognitive, neurophysiologic, and perceptual ones (Brazález, Iparraguirre, & Puerta, 2018) and does not have a uniform definition. Moray (1979) e.g., defines mental workload as the number of task demands addressing the cognitive resources of a human. Eggemeier, Wilson, Kramer, & Damos (1991) define it as "the portion of operator information processing capacity or resources that is required to meet system demands." (p. 207). Xie & Salvendy (2000) also include the factor time in their definition and state that mental workload is the amount of effort needed to complete a given task over a specific time period.

Examining mental workload is important for understanding the human's performance in different situations as the relationship between e.g. driving task demands, human capacity, and performance has been shown in various studies. According to Kantowitz & Simsek (2001), there is a direct relation between the risk of an accident and the driver's mental workload. In the automotive context, the amount of mental workload can vary greatly, as drivers must process a large amount of different information coming from inside and outside of the vehicle (Baldwin & Coyne, 2003; Verwey, 2000). Additionally, mental workload can be influenced by the physical and emotional state, motivation to perform the current task, strategies applied on task performance, and personal characteristics of the driver (e.g. driving experience or age) (Brazález et al., 2018).

In case of AR HUD concept design, developers have to make sure to find solutions that are intuitive and easy to process for the majority of drivers, so that the available mental resources do not get overstrained.

2.5 Driver Distraction

The primary driving task (including steering, stabilization, and navigation as well as secondary driving-related activities, like speedometer- or mirror-checking) require a high amount of perceptual, cognitive, and manual resources. In particularly challenging traffic situations, the required workload could exceed the driver's mental resources which might lead to *driver distraction*. Additionally, the driver's attention can be drawn to other traffic events, like a crash on the other lane. Furthermore, road users can get distracted by undertaking non-driving related activities, like talking to a passenger, tuning the radio, making a phone call, or eating. Finally, drivers could become tired while driving or daydream without being necessarily tired, which can distract them as well (European Road Safety Observatory, 2018).

According to (Pettitt, Burnett, & Stevens, 2005), different approaches for defining driver distraction exist. John Lee, Young, & Regan (2008) give a general definition of the term *driver distraction* that is based on an analysis of common parts in different definitions and interpretations of distraction:

> "Driver distraction is the diversion of attention away from activities critical for safe driving toward a competing activity." (John Lee et al., 2008, p. 34)

Hedlund, Simpson, & Mayhew (2005) define the term based on the common opinion of a group of experts in the field of driver distraction that met at the *International Conference on Distracted Driving*:

> "a diversion of attention from driving, because the driver is temporarily focusing on an object, person, task, or event not related to driving, which reduces the driver's awareness, decision-making ability, and/or performance, leading to an increased risk of corrective actions, near-crashes, or crashes" (Hedlund et al., 2005)

Various sources can cause driver distraction which can be classified in four different categories: *Visual distraction* (e.g. looking away from the road scene), *auditory distraction* (e.g. listening to a passenger), *manual distraction* (e.g. manually searching for a radio station), and *cognitive distraction* (e.g. daydreaming). Many activities that might distract road users include more than one of these categories. One example could be the visual search for a control inside the car which the driver wants to adjust. The usage of media devices while driving has the potential to distract the road user in each of the four ways mentioned above (Lees & Lee, 2007). Further, actions like having a conversation or listening to the radio could affect the driver's mindset or mood and thereby, his or her driving behaviour (European Road Safety Observatory, 2018).

The easiest way to assess distraction is to simply ask drivers about their degree of feeling distracted. Humans are normally able to correctly assess their psychological state together with their mental resources (Pauzié, 2014). Harmful effects of secondary tasks on driving performance are sometimes underestimated (Young & Regan, 2007). Furthermore, subjects can only be interviewed after the actual task and thus, memory gaps might occur. Hence, it is advisable to also consider objective data to assess distraction: One method could be the evaluation of physiological makers, e.g. assessing eye glances, visual occlusion, heart rate variability, and skin resistance (Heiner Bubb, Bengler, Lange, Aringer, & Truebswetter, 2015; Wu, 2009). Another method is the measurement of various aspects of driving performance that correlate with distracted driving. These measures include actions that are required for completing the primary driving task, such as lane-keeping, the omission of direction indicators, or navigation errors. Also, actions that are taken to compensate high perceptual and cognitive requirements, such as reducing vehicle speed or the usage of less busy lanes (European Road Safety Observatory, 2018; Theofanou, 2002; Wu, 2009).

However, one should stress that researchers should not just use a single metric to assess driver distraction, but rather an interplay of subjective, physiological, and behavioural data.

3 Driving Task and Driving Assistance

The AR HUD can support drivers with content displayed in their primary FOV, but concept developers have to be careful to not overextend users with too much information. Thus, only use cases that support drivers with the primary navigation task should be integrated and are usually part of navigation or driving assistance. This chapter describes the elements of the driving task and gives an overview of *advanced driver assistance systems* (ADASs). Special emphasis is placed on the navigation task together with a brief description of already existing navigation systems, as in this work a concept for the use case navigation will be developed.

3.1 The Driving Task

The driving task is a complex task with high demands on the driver, which can be subdivided into different subtasks. These subtasks can be hierarchically arranged or can be independently from another.

According to Rasmussen (1983), target-oriented tasks like the driving task can be assigned to three different levels regarding the demands on the person's cognitive resources: In situations where the human is suddenly confronted with complex, rare tasks and could not train those before, *knowledge-based behaviour* is required. Typical for this behaviour is that the person has to choose between different action alternatives and test them for suitability for the current task, based on existing knowledge or knowledge that still has to be acquired. The time needed for that is in the range of a few seconds to some days or more. The chosen behaviour can be stored as a behavioural pattern for similar situations that might occur in the future. *Knowledge-based behaviour* causes heavy demands on the human's cognitive resources. The next level represents the *rule-based behaviour*. This behaviour is shown when the person has experienced similar situations before and has built a repertoire consisting of stored rules or procedures from which he or she can select the most suitable one for the current task. The processing time for those is in the range of one to two seconds. Finally, there is the *skill-based behaviour* which includes routine activities that are well trained, take place without conscious control, and have been executed many times before. The reaction time for those actions is around 200ms. This behaviour pattern causes low demands on the cognitive resources and in general, it is even possible to perform additional side tasks that are not related with the current routine activity (Heiner Bubb, 2015a; Rasmussen, 1983).

As described by Geiser (1985), the driving task can be subdivided in *primary*, *secondary,* and *tertiary driving task,* whereby the importance of the task is shown by the hierarchy as well. The *primary driving task* is defined as the act of transporting persons or goods from one location to the other at a definite time. To achieve this goal, the driver has to perform several subtasks as described by Bernotat (1970). First, he mentions the *navigation task* which contains the planning of the route, the estimation of the travel time and the choice of the trip's starting time. Furthermore, the driver has to react to interferences like a traffic jam or a road closure and if necessary, change the route. The next subtask of the *primary driving task* is called *vehicle guidance* which requires the driver to determine the desired velocity and track, depending on the current traffic conditions. Those values can be decided in accordance with external factors as weather conditions, road course, obstacles on the roadway, traffic density, and the behaviour of other traffic participants. To maintain speed and course, the driver needs to perform different stabilisation tasks which can be carried out by the usage of the vehicle's control elements. These stabilisation tasks contain the regulation of longitudinal and lateral dynamics of the vehicle (Heiner Bubb, 2015b). Actions that are carried out by drivers to show other road users what they do next or to react to outer conditions are part of the *secondary driving task* and are connected to the *primary driving task*. An action to inform others could be e.g. the usage of the indicator before changing the lane or warning other traffic participants of possible danger by using the horn. Examples for reactions to external conditions could be switching between full and dipped beam or turning on the windscreen wiper in case of rain (Heiner Bubb, 2015b). *Tertiary driving tasks* are not connected to the actual driving task and refer to tasks such as infotainment and communication systems, operating comfort, or eating and drinking. With increasing automation and driving assistance, the vehicle will take over some or all of the primary and secondary driving tasks in the near future which will direct the focus toward the tertiary tasks (Pfleging & Schmidt, 2015).

Primary, secondary, and tertiary driving tasks can be put in different areas of the cockpit which is illustrated in Figure 3. Information for primary tasks is displayed best directly in the HUD as these tasks require direct interaction with the surrounding world. The driver is able to control primary tasks with the help of devices that are in a comfortable distance for arms and legs, such as steering wheel, gas, or brake pedal. Information related to the secondary driving task should be located in a distance that is close to the focal perspective and still easily reachable for the human. The area below the vehicle's windshield that surrounds the steering wheel is suitable. Functionality concerning the tertiary driving task is placed more to the vehicle's centre, next to the secondary information. This location allows the information to still be accessible while not distracting the human from perceiving information that is more important for driving. However, there can be exceptions for functionalities that are used frequently. These should be accessible immediately and thus, be located in the area of the primary or secondary tasks (Geiser, 1985; Toennis, Broy, & Klinker, 2006).

Figure 3: Allocation of primary, secondary, and tertiary driving task (Toennis et al., 2006).

Hale, Stoop, & Hommels (1990) connected the primary, secondary, and tertiary driving task with the *three levels of driving task* described by Rasmussen (1983) and gave suitable situations in the driving context for each combination (cf. Figure 3).

	Planning	**Manoeuvre**	**Control**
Knowledge	*Navigation in strange town*	*Controlling a skid on icy roads*	*Learner on first lesson*
Rule	*Choice between familiar routes*	*Passing other cars*	*Driving an unfamiliar car*
Skill	*Home/work travel*	*Negotiating familiar junctions*	*Road holding round corners*

Table 1: The three levels of the driving task in relation with the primary, secondary, and tertiary driving task (Hale et al., 1990).

3.2 Advanced Driver Assistance Systems

A*dvanced driver assistance systems* (ADASs) are systems created to "automate, adapt, and enhance vehicle systems in order to increase safety and better driving." (Dimitrakopoulos, 2016, p. 63). ADASs are either primarily designed to support drivers and thus, called *driver support systems* (e.g. vision enhancement, navigation systems, and automated transactions) or to support the vehicle and subsequently referred to as *vehicle support systems* (e.g. lane departure prevention, speed control, and obstacle detection) (Golias, Yannis, & Antoniou, 2002). Many studies have shown that the number of traffic accidents could be reduced due to the integration of ADASs in vehicles (Golias et al., 2002; Jermakian, 2011; Kahane & Dang, 2009; Kuehn, Hummel, & Bende, 2009; National Highway Traffic Safety Administration (NHTSA), 2000, 2005). The technologies *antilock brake systems* (ABS) and *electronic stability control* (ESC) e.g., prevent a large number of crashes (Kahane & Dang, 2009) and are now prescribed by law for new cars (VDI Wissensforum GmbH, 2019). There are further optional ADASs that are expected to reduce emissions and road fatalities (eSafety Forum, 2008; van Calker & Flemming, 2012). According to VDI Wissensforum GmbH (2019), these systems are called *priority systems* and can be classified as follows:

- *Lane Keeping Support Systems* (warn road users when they leave a lane accidentally)
- *Obstacle and Collision Warning Systems* (responsible for detecting obstacles in the street and warn the driver about a possible collision)
- *Emergency Braking Systems* (responsible for detecting obstacles, warning the drivers in case of an imminent collision, and doing an emergency brake)
- *Blind Spot Monitoring Systems* (use camera technologies with radar or image processing and thus, give a better vision into the blind spot area)
- *Adaptive Headlight Systems* (make optimum illumination in bends possible by using headlights that are controlled in an electromechanically way)
- *Eco Driving Support Systems* (assist the road users with driving in a more economically friendly way by providing supplementary information, such as correct gear selection or current fuel consumption)

3.3 The Navigation Task

A detailed understanding of the driver's tasks is required when developing any kind of innovative automotive user-interface. In the following, the term *navigation* will be explained in detail.

Burnett (1998) describes navigation as a continuous task. The corresponding model contains the following stages: *Planning*, *preview*, *identify*, *confirm*, *confidence*, and *orientation* (cf. Figure 4). This definition is well supported by Lee, Forlizzi, & Hudson (2008) and Ross & Burnett (2001). At each of the single stages, the driver has different goals which are part of the overall navigation task. During the first stage, *planning*, the driver chooses and plans the route, which typically takes place before starting the trip. The next three stages are directly relevant for taking the route's turns. The *preview* stage happens directly prior to an upcoming manoeuvre and comprises the creation of a mental model of the manoeuvre. In the next stage, *identify*, the required location, speed, and positioning will be determined. Finally, the driver wants to make sure whether the correct manoeuvre has been recognised and whether a navigation error has been made (the *confirm* stage). The next two stages happen during the navigational task and are called *confidence* and *orientation*. During the *confidence* stage, the driver gains reassurance that he or she is still following the right track and makes sure that the system is still working without any problems. The final stage, *orientation*, describes the process of checking current direction and location within the driver's general surroundings.

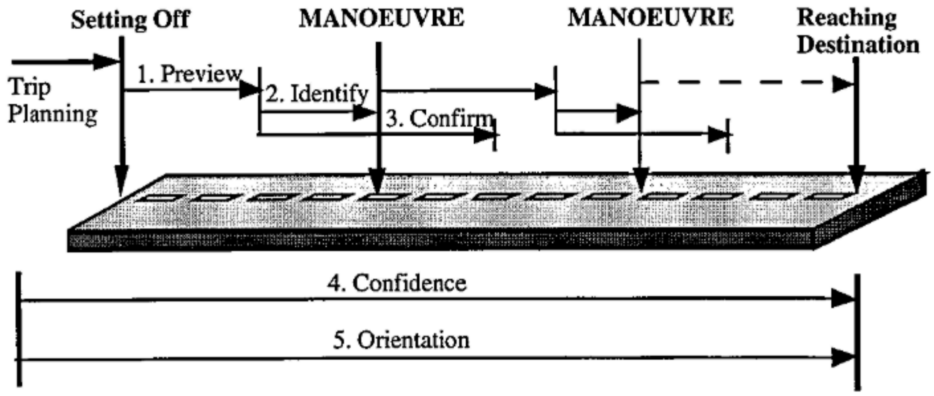


Figure 4: The stages of the navigation task (Burnett, 1998).

3.4 Navigation Systems in Today's Motorcars

As part of Daimler's multimedia system *Mercedes-Benz User Experience* (MBUX), AR technology was integrated into the navigation system (cf. Figure 5). This advancement was released for the first time in 2018, as part of the *Mercedes-Benz A-class (W177)*. The so-called *augmented video system* (AVS) displays a conventional map when no navigation instructions are given. When approaching an upcoming manoeuvre, however, the traditional map will be replaced by a real-time video of the environment, which is recorded by the vehicle's front camera. The video is displayed on the central display and will be augmented in a contact analogue way with virtual elements, such as cyan navigation arrows indicating the street to turn into. To indicate the remaining distance to the upcoming manoeuvre, a static white arrow is shown together with the distance value. Furthermore, the system shows street names as well as house numbers placed at the location of the corresponding building. In addition to the video frame, a zoomed-in map view is displayed on the left side (Daimler AG, n.d.; Dirscherl, 2019; Mbpassion, 2018). The benefits of such video-based AR navigation systems over a conventional map-based navigation system have been shown in various studies (e.g. Akaho et al., 2012; Narzt et al., 2006).

Figure 5: The augmented video system (AVS) by Mercedes-Benz (Daimler AG, n.d.).

4 Augmented Reality Head-up Displays

In this chapter, the advantages of conventional HUDs over HDDs are explained. Furthermore, an explanation of the term *augmented reality* is given and technical basics of HUDs and AR HUDs are described. Also, the benefits of AR HUDs are summarised together with challenges that developers and designers still have to deal with.

4.1 A comparison of HDDs and HUDs in the Vehicle

In a vehicle, information can be provided to the driver in multiple ways. Two examples are a *head-down display* (HDD) as well as a *head-up display* (HUD).

The HDD displays relevant information below the driver's line of sight, normally on the dashboard or middle console. This location forces the driver to accommodate the eye and to avert the gaze from the road and thereby, divert the visual attention away from traffic events (Liu & Wen, 2004). Zwhalen, Adams, & DeBald (1988) explained that if a driver's gaze leaves the street for more than two seconds, the risk for a traffic accident increases significantly. Situations like this are one of the main reasons for dangers in traffic (Wierwille, 1995). Today, all vehicles are equipped with HDDs, while the interest in the HUD technology is growing.

In the following, advantages and disadvantages of a conventional HUD are described while an overview is given in Table 2. An HUD provides information close to the driver's natural line of sight. An important advantage of this technology is that the human can use ambient or peripheral vision to view the environment that surrounds the display (Smith, 2018). Also, the angle between virtual information and the current driving scene is much smaller than in case of an HDD and thus, the driver is not forced to look down (Gabbard et al., 2014). This leads to a time advantage from up to 100ms per fixation when the head movement is taken into account (Kloke, 2005), which equals around three meters when driving with 100 km/h. Further, the accommodation and adaption effort for drivers decreases when driving with a HUD as the human eye does not have to adapt to different distances and lightning conditions inside and outside of the vehicle (Milicic, 2010). Thus, visual fatigue effects can be reduced. This is especially an advantage for older drivers, as the ability to accommodate the eye decreases with age. An experiment conducted by Kiefer (1999) showed that older humans recognise unexpected traffic events significantly faster when driving with an HUD, compared to an HDD. Further, in a simulation study, Liu & Wen (2004) showed that HUDs could have an advantage over HDDs regarding response time to urgent events and variability of speed control. Also, participants had less mental stress when using a HUD. Furthermore, Smith (2018) found out that participants driving with an HUD were able to maintain better vehicle control while performing visual search tasks compared to driving with an HDD. Next, the participant's workload was lower when using the HUD while, at the same time, they felt less distracted and generally favoured the HUD over the HDD.

Nevertheless, the usage of conventional HUDs is also connected with risks. Displaying virtual information in the driver's primary FOV can lead to masking of the real-world environment (Gish & Staplin, 1995). The danger of masking occurs especially when a big amount of information is shown in the HUD. In these scenarios, the driver's attention can be guided inadvertently to the virtual content and thus, other traffic events might not be noticed (Atchley, Kramer, Andersen, & Theeuwes, 1997). Another negative effect that can be caused by HUDs is called *cognitive capture*, i.e. an unconscious shift of attention away from traffic towards the virtual information shown in the HUD. This phenomenon is related to a slower detection and reaction to critical traffic events and can make a shift of attention back to the real world more difficult (Gish & Staplin, 1995; Milicic, 2010). According to Gish & Staplin (1995), *cognitive capture* effects mainly occur when the mental workload of the driver is high and when quick reactions to unexpected traffic events are necessary. Another potential risk related to HUDs is *perceptual* or *attentional tunnelling* which describes the narrowing of the peripheral FOV and accordingly, the limitation of the peripheral vision. This is caused by focusing on a particular stimulus like the virtual content displayed by the HUD (Bossi, Ward, Parkes, & Howarth, 1997) longer than recommended or needed (C. D. Wickens & Alexander, 2009).

Advantages	**Disadvantages**
Information is displayed in the primary FOV	Masking of real-world objects
Peripheral vision can be used to view surrounding events	Cognitive capture (shift of attention towards virtual information)
Small angle between current driving scene and virtual content	Perceptual or attentional tunnelling (narrowing of peripheral FOV)
Less accommodation effort of the eyes needed	

Table 2: Advantages and disadvantages of conventional HUDs.

4.2 Augmented Reality

Augmented reality (AR) describes the extension of the real-world environment with virtual, computer-generated information (Azuma, 1997; Azuma et al., 2001). The fusion of the real environment with virtual graphics can provide additional information which is not accessible to the human otherwise. The first person that realised AR was Ivan Sutherland. After mentioning that further advances in computer technology will make it possible to complement the human senses by virtual content (Sutherland, 1965), he developed the first "augmented reality system using an optical see-through head-mounted display" (Furht, 2011).

Later Azuma (1997) came up with one of the most popular definitions of augmented reality. He defines AR as a system that has the following three characteristics: Firstly, it combines reality and virtuality. Secondly, the system is interactive in real-time and thirdly, the AR content is registered in three dimensions. In literature, one can find various other definitions for the term *augmented reality* that are contradicting at times. Schueffel (2017) defines it as follows:

> "Augmented reality is an enhanced version of the physical, real-world reality of which elements are superimposed by computer-generated or extracted real-world sensory 3 input such as sound, video, graphics or haptics." (Schueffel, 2017, p. 3)

Another definition of AR is given by Carmigniani & Furth (2011):

> "We define Augmented Reality (AR) as a real-time direct or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it." (Carmigniani & Furth, 2011)

Milgram, Takemura, Utsumi, & Kishino (1994) described a continuum between reality and virtuality where one can find the real environment at the one end. As shown in Figure 6, there is the virtual environment at the one side that represents a synthetic world which could have or not have the properties of a real-world environment. Also, limitations like physical laws or time could be switched off. Anywhere between the two extrema of the *reality-virtuality continuum,* a so-called *mixed reality environment* is defined in which real and virtual content exist in the same world and are presented in the same display. The mixed reality environment can be divided into different classes again. When the percentage of real-world objects is higher than the percentage of virtual objects, one talks about an *augmented reality environment*. The other way around the system can be defined as an *augmented virtuality environment*.

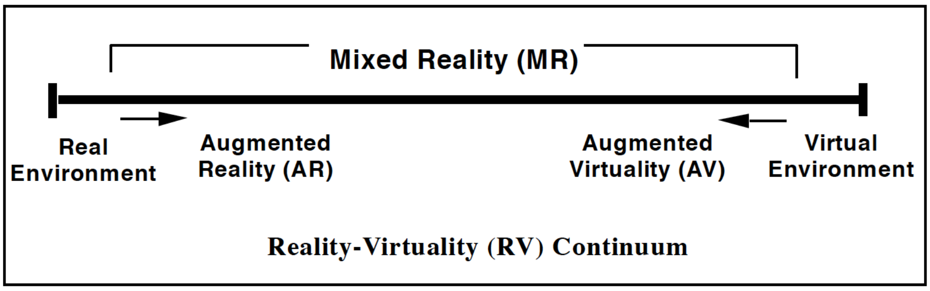


Figure 6: Representation of the Reality-Virtuality Continuum (Milgram & Kishino, 1994).

Today, the AR technology is applied in various areas such as medicine or medical training (e.g. Fischer, Neff, Freudenstein, & Bartz, 2004; Furht, 2011; Harders, Bianchi, & Knoerlein, 2007; Kilgus et al., 2015; Vorraber et al., 2014), entertainment or video games (e.g. Thomas et al., 2002), as well as commercial diving (e.g. Morales, Keitler, Maier, & Klinker, 2009). Further potential areas of applications include teleoperation of robots (e.g. Chintamani, Cao, Ellis, & Pandya, 2010), tracking underground infrastructure (e.g. Schall et al., 2009), and pedestrian navigation (e.g. Mulloni, Seichter, & Schmalstieg, 2011; Pingel & Clarke, 2005; Rehrl et al., 2012; Schinke, Henze, & Boll, 2010). Also, engineering and interior design (e.g. Tang, Owen, & Biocca, 2003) as well as manufacturing processes (e.g. Carmigniani & Furth, 2011; Caudell & Mizell, 1992; Hahn, Ludwig, & Wolff, 2015; Nee, Ong, Chryssolouris, & Mourtzis, 2012), or fashion (e.g. Borko Furht, 2011) belong to that list.

Another meaningful application field for AR is the automotive sector. In a vehicle, AR content can be shown both on an HDD and HUD. In case of a traditional HDD the real world is recorded as a video and the virtual information is overlaid afterwards. *Daimler AG* has realised an exemplary system, which was further explained in Section 3.4, as part of the multimedia system *MBUX* (Daimler AG, n.d.). When using an AR HUD, the driver looks directly at the real-world environment with rendered images projected onto the windshield (Smith, 2018).

4.3 Technical Foundations of Head-up Displays

In the following, the fundamental functional principle of a HUD is described and illustrated in Figure 7. Furthermore, an overview of different AR HUD technologies is given.

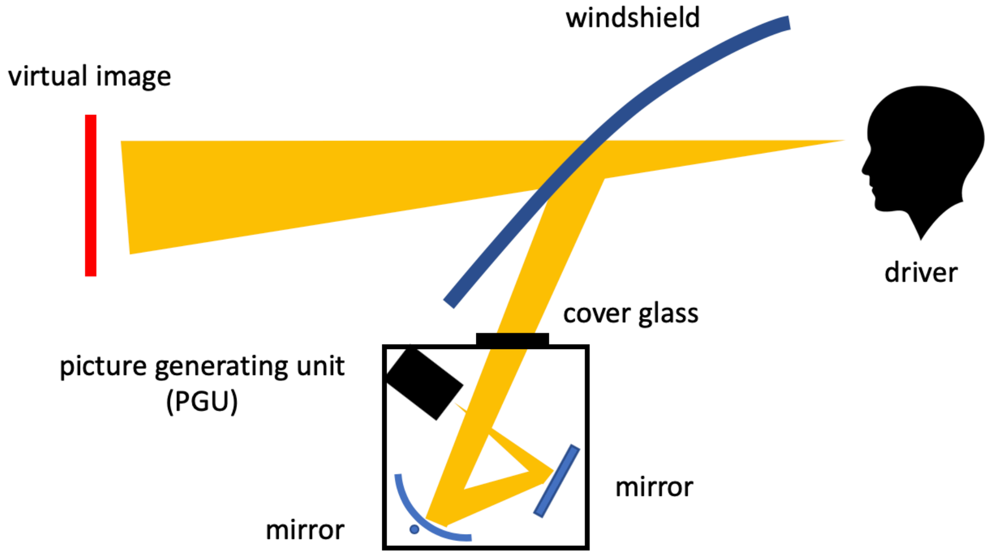


Figure 7: The basic functional principle of an HUD (Schneid, 2009, p. 7).

A HUD always consists of an image source, an optical system, and a transparent mirror which can be the windshield in a vehicle. The optical system produces an enlarged virtual image by deflecting the light beams generated by the picture source. Next, the light ray comes out of the HUD's coverslip and hits, e.g. the windshield of the vehicle, which makes it possible for the driver to see the reflected image. This virtual information is overlapping the real world in the driver's primary FOV (Israel, 2013, p. 24; Schneid, 2009, pp. 3-6). In today's motorcars one usually finds *liquid crystal displays* (LCDs), *vacuum fluorescent displays* (VFDs), *laser display technology* (LDT) displays, or *digital light processing-projectors* (DLP projectors) as image source (*picture generating unit* [PGU]) but basically any light-emitting unit could be used. It is important that the image source, which is installed in the instrument panel, can generate an image that is as bright as possible (> 10.000 cd/m^2) and rich in contrast. To adapt to different light conditions, the brightness of the picture should be adjustable. Furthermore, requirements regarding impact and temperature resistance as well as production costs have to be met (Israel, 2013 p. 48; Pfannmüller, 2017, p. 31). The optical system contains one or more lenses or mirrors (plane, concave, or convex) which enlarge the image source and increase the virtual image's distance. Furthermore, the optical system is responsible for folding or deflecting the beam path to keep the installation space required for the HUD as small as possible. This is especially important in the automotive context regarding the small space available in a car's frontal area. The folding of the optical path and a more flexible positioning of the object displayed can be achieved with the help of plane mirrors. A convex lens or magnifying glass is thicker at the middle than at the edges and produces a magnified, upright virtual image which is on the same side of the lens as the object. The distance between lens and object has to be shorter than the focal length, so that the image can be observed. This lens type is used in the context of HUDs to enlarge the virtual picture and to increase the distance in which it is perceived by the human. Also, the usage of concave mirrors can lead to a magnified image with a larger distance. The difference to a lens is that the object is on the same side as the focal point and the virtual image on the other (Israel, 2013, pp. 21-23; Pfannmüller, 2017, p. 31; Schneid, 2009, pp. 4-6).

The *combiner*, a transparent mirror, on which the virtual image is projected can be a separate pane that is usually a concave mirror. This mirror is placed between steering wheel and windshield. However, for aesthetic reasons, the windshield is often used as a combiner in vehicles. In a transparent mirror, the real world and the mirror image are visible at the same time and as in a mirror the perception distance equals the length of a light path, the image appears outside of the vehicle. When the windshield is used as a combiner display, it is a component of the optical system and therefore directly influences the virtual image quality. One disadvantage is that double pictures are generated by the reflection on both sides of this transparent mirror. To prevent this, a wedge-shaped film has to be used to stick both parts of the laminated glass together in a way that both light beams overlap and the two pictures are seen as one (Israel, 2013, pp. 21-25; Pfannmüller, 2017, p. 31). Schneid (2009, pp. 14-16) describes the calculation of the angle between the two parts of the laminated glass, which is dependent on the angle of the projector to the pane, the slice thickness of the glass, the refractive index of the glass type, and the distance of the virtual image. The mentioned parameters differ for each carline with a HUD, as its optical system is unique. Therefore, new calculations for the wedge-shaped film need to be done for every model. An example for this is a study conducted by Wagner et al. (2020) in which the impact of the windshield geometry on the subjective driver perception was investigated. The work indicates that inhomogeneous image quality disturbs the driver.

The *eye box* is the area in which the driver's eyes must be located to recognise the displayed virtual image. According to Schneid (2009, p. 6), the *eye box* is defined by the size of the optical elements and the outlet nozzle.

The integration of the AR technology into a HUD in a passenger car was realised for the first time by Bubb (1975) and can be seen as an advancement of the conventional HUD. With an AR HUD, it is possible to display virtual content in a contact analogue way directly in the primary FOV of the driver.

One approach to realise this system is to project a lying or slightly inclined virtual picture in the depth of space. This can be done with the *Scheimpflug Principle* which is a geometric rule that describes the orientation of an optical system's plane of focus when image and lens plane are not parallel to each other (Israel, 2013). Bubb (1975) is using this principle to develop an AR HUD with a virtual image directly projected on the street and Schneid (2009) refined it by adding a curvature towards the horizon to the virtual image plane.

Another approach to realise an AR HUD is to display information on a standing image plane. When using this technology, the distance of virtual content is faked by solely using image-related monocular depth cues (Bergmeier, 2009). The functionality of this approach is comparable with the one of a conventional HUD as the virtual image is not projected in the depth of space but displayed on a 2D virtual plane. Today, a system with a standing virtual image plane has been realised, e.g. by Continental AG (2019) with a distance of 7.5 meters. Figure 8 illustrates both a lying and a standing virtual image plane.

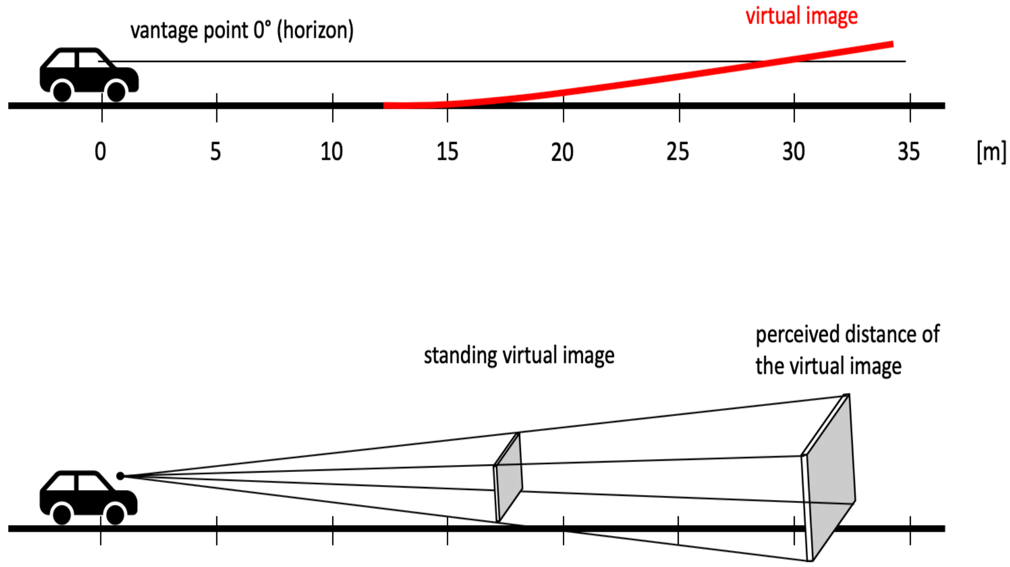


Figure 8: Lying image plane (cf. Schneid, 2009) and standing image plane (cf. Bergmeier, 2009).

Furthermore, there is an approach that uses the principle of stereoscopy. Unlike the approaches with a standing and lying image plane, this technique uses two optical systems together with two separate eye boxes while each eye sees a slightly different picture (Nakamura et al., 2004). Thus, the illusion of depth is created. Figure 9 illustrates the fundamental functionality of a stereoscopic HUD. However, two different eye boxes have the disadvantage that both eyes have to be located in a fixed position without great flexibility. Already small deviations of the defined position destroy the stereoscopic effect. For this reason, this approach has not been established in the automotive context and is more suitable for wearable systems like AR glasses.

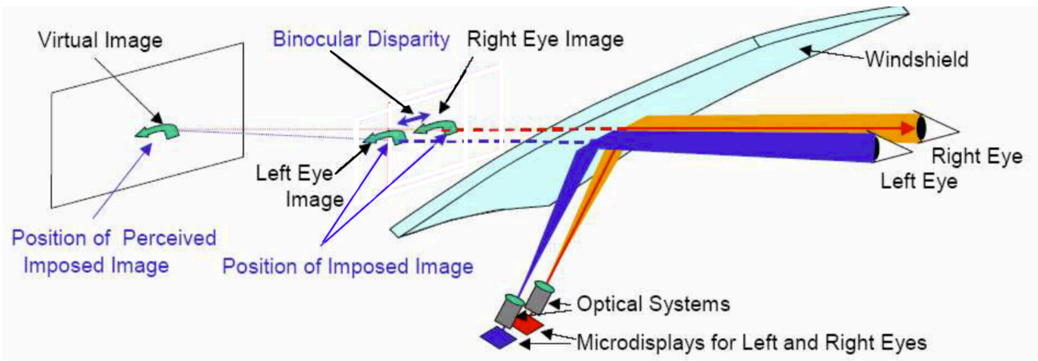


Figure 9: The functionality of a stereoscopic HUD (Nakamura et al., 2004).

4.4 Benefits and Limitations of AR HUDs

With an AR HUD, it is possible to display virtual information in a contact analogue way directly in the primary FOV of the driver. This technology brings a lot of benefits concerning security and comfort, but also some risks. Table 3 gives an overview of all benefits and limitations which are described in more detail in the following.

The most obvious advantage of an AR HUD is that virtual information is displayed in the direct line of sight of drivers, like in a conventional HUD. Consequently, there is no need to avert the gaze from the road. Additionally, the virtual information is connected to and overlaid on objects of the real world and thus, drivers do not have to shift their attention away from traffic. Furthermore, due to the spatial proximity of virtual content and objects it refers to, divided attention can be reduced (Gabbard et al., 2014). Visual information displayed in an AR HUD can even be used to guide the driver's attention towards relevant events like navigation cues, dangers, or points of interest like, e.g. destination and parking spots. (Gabbard et al., 2014). This can lead to faster reactions of the human, which is especially important in critical driving situations. Concerning accommodation, AR HUDs require even less effort than conventional HUDs as the virtual information is displayed in greater distance and thus, in a similar image plane as the real objects it is overlaid on (Gabbard et al., 2014).

When using AR HUDs in the automotive context, there are still challenges to master. One of them is the process of tracking to position contact analogue information at the correct location in the real world. An overview of various tracking approaches is given by Rabbi & Ullah (2013). In case of AR HUDs, tracking has three main problems: The first one is the process of calculating the position and orientation of the vehicle. The second problem is determining the location of the driver's head inside the car and the third one is the tracking and identification of objects of the real-world environment like vehicles or pedestrians (Gabbard et al., 2014). Furthermore, the usage of HUDs in the automotive context leads to challenges concerning colour perception. These are caused by the fact that the driver sees a combination of synthetic coloured light, like the AR content and real-world light which can make it hard to recognise and read the virtual information (Kerr et al., 2011; Peterson, Axholt, & Ellis, 2008; Pingel & Clarke, 2005). Besides, developers have to keep in mind that the lighting conditions of the real-world environment vary significantly from a night-time drive to a sunny day. Also, the visual complexity of the real world can change continuously as there are visually rich city scenes and monotonous country road sections which can lead to usability problems, such as bad legibility of the AR content (see Gabbard, Swan II, & Hix, 2006). Driver distraction is another challenge that has to be dealt with in AR HUD development. Distracted driving diverts the human's attention away from the primary driving task and contains visual distractions (e.g. looking at the AR content), manual distractions (e.g. interacting with the AR content via buttons on the steering wheel), and cognitive distractions (e.g. processing and interpreting AR content) (Gabbard et al., 2014). According to Gish & Staplin (1995), AR HUDs might capture the driver's attention away from the traffic scene in moments of uncertainty and high workload. At the same time, drivers could focus only on the AR content and fail to direct their attention back to the real-world environment when necessary, e.g. in case of pedestrians crossing the street (C. D. Wickens, Pringle, & Merlo, 1999; Yeh, 2000). Finally, an AR HUD concept developer has to keep in mind that displaying too many elements in the primary FOV causes masking of real-world objects and traffic events. Thus, developers have to make sure that only essential and driving relevant information is shown in AR displays (Gabbard et al., 2014; Gish & Staplin, 1995). Section 7.1.2 gives a detailed description of the current state of research concerning masking in AR HUDs.

Benefits	Limitations
Virtual content is displayed in the direct line of sight	Inaccurate positioning of virtual content due to tracking problems
Virtual content is connected to real objects in a contact analogue way	Difficulties with perceiving the right colour of the virtual content
Divided attention can be reduced	Driver distraction caused by virtual content
Driver's attention can be guided in a meaningful way	Masking of real-world objects
Less accommodation effort is required	

Table 3: Benefits and limitations of AR HUDs.

5 Design Principles

In this section, an overview of various design principles which are important for AR HUD concept design is given. First, an overview of the *Gestalt laws of perceptual organisation* is given, which make it easier for the driver to recognise relations between visual content. Secondly, HMI design guidelines for automotive systems are described and lastly, guidelines for AR HUD concept design are explained.

5.1 The Gestalt Laws of Perceptual Organisation

The phenomenon that a group of elements can seem to be one larger object is comprised in the *Gestalt laws of perceptual organisation* (Goldstein, 2009). These principles play an important role when processing visual information as they can facilitate the search for information and clarify relations. According to Preim & Dachselt (2010), the processing time for visual search tasks decreases when applying these principles. Additionally, balance and aesthetics of the displayed information are enhanced. In the following, the *Gestalt laws of perceptual organisation* are listed and described:

- **Praegnanz**: The *law of praegnanz*, also called the *law of simplicity* or the *law of good figure*, is the main law of *gestalt psychology*. It describes the fact that every pattern of a stimulus is perceived in a way that the resulting construct is as simple as possible. One example to clarify this law would be the *Olympic symbol*, which is seen as five single rings and not as a bigger amount of more complicated shapes.
- **Similarity**: The *law of similarity* involves that things that have the same colour, shape, or orientation seem to belong together. Grouping also appears for auditory acoustic stimuli. Notes that follow each other directly or have a similar pitch can occur as a group.

- **Good continuation**: According to the *law of good continuation*, connected points that seem as straight or slightly curved lines are perceived as belonging together. Furthermore, the lines seem to follow the easiest or smoothest path.
- **Proximity or nearness**: The *law of proximity* or *nearness* explains that objects that are close to each other occur to be grouped together.
- **Common region**: The *principle of common region* involves that objects that are in the same region of space seem to belong together. This region could be marked by a circle drawn around single elements.
- **Uniform connectedness**: The *principle of uniform connectedness* explains the phenomenon that a connected region of visual properties, like motion, colour, texture, or lightness does appear as one element.
- **Synchrony**: The *principle of synchrony* explains that visual elements that appear at the same time are perceived as a group. An example could be LEDs that are blinking synchronously.
- **Common fate**: The *law of common* fate states that elements that move in the same direction seem to belong together. A swarm of birds could be a typical example for this.
- **Meaningfulness or familiarity**: The *law of familiarity* states that elements which form familiar or meaningful objects, are likely to be seen as a group (Hochberg, 1971).

5.2 Design Guidelines for HMI in Vehicles

This section contains ergonomic standards and guidelines for concept design in the automotive context. The described guidelines apply in particular to HDDs but should also be considered when developing HUD concepts.

ISO 15005 (International Organization for Standardization, 2017b) contains ergonomic fundamentals regarding the development of dialogues between driver and systems in the vehicle. All systems and functions of the vehicle must be created in a way to not distract or overextend the human while driving and to not require the driver’s attention for a longer time. It is recommended to display information in small, consistent, and clear amounts. Furthermore, the driver has to be able to leave at least one hand on the steering wheel and to keep control over the systems that are currently in use. Thus, the interaction with the current system has to be interruptible at all times.

ISO 15008 (International Organization for Standardization, 2017a) provides information concerning the size and location of the displayed information, contrast relations, colour selection, and reflections. However, the HUD cannot be compared to other automotive displays due to its semi-transparent way of displaying information outside the vehicle. Thus, the guidelines given in ISO 15008 cannot be considered.

The *European Statements of Principles* (ESoP) describe the recommendations of the European Commission regarding the design of *transport information and control systems* (TICS) and contain fundamental conditions for the design of *human-computer interaction* (HCI) in vehicles (Commission of the European Communities, 2008). However, HUDs are not addressed specifically, but the presented design goals also apply for this technology:

- **Design goal I**: The information system should be designed in a way to support the user with his driving task. It should not confuse, mislead, or distract the driver and enhance driving safety.
- **Design goal II**: As the human's attentional resources are limited, developers should make sure to not overextend the driver by requiring too much attention for the interaction with system displays and controls. Thus, the user still has enough attentional resources to meet the requirements of the driving task.
- **Design goal III**: The user should not be distracted or visually entertained by a driver information system. This may be caused by displaying images that capture the driver's attention due to their content or form.
- **Design goal IV**: The content shown by the information system should not encourage the driver to behave in a way that makes an accident more likely, e.g. by displaying a racing line with a corresponding measurement of time.

- **Design goal V**: All HMI systems available in the vehicle should be designed in a compatible and consistent way, e.g. when an ADAS information is displayed on more than one information system. Among others, consistency can be achieved by using similar menu structures, common terminology, and certain icons, colours, sounds, or labels.

Ross et al. (1996) provide guidelines for designers of *advanced transport telematics systems* (ATT systems) to support them with the development of user-friendly and safe technology that displays information to the driver. In the following, a selection of guidelines that address visual road and traffic information and are relevant for this work are described:

- The usage of traffic-related symbols or icons should be preferred over text messages as they require less reading effort and thus, can be perceived faster.
- The understandability of a symbol with an important meaning should be tested among a group of possible future users to make sure that everyone interprets it the same way.
- Text messages should be kept short and unambiguous. Furthermore, the efficiency in reading and understanding the textual content should be evaluated with future users.
- When using textual content, decorative letters and styles should be avoided to enhance legibility.
- The usage of abbreviations should be avoided when there is enough space available as the understanding of abbreviations can require more time.
- Whenever possible, both visual and auditory information should be available to the driver. Studies have shown that additional auditive information decreases the user’s visual checking of the screen.

- While the vehicle is moving, traffic-related information should be shown in a simple way, but whenever possible, more detailed information concerning location and type of the current event should be available.
- Symbols are preferred to textual messages to show the location of the current road event. Thus, international understanding is possible and information can be processed faster.

5.3 Design Guidelines for Head-up Displays

Milicic (2010) defined a set of concept and interaction design guidelines for HUDs, based on conducted experiments, literature, and experience with virtual display surfaces. Although these guidelines were defined for a conventional HUD, most of them are also useful when creating concepts for an AR HUD. In this section, however, only the design rules for concepts are described as this work does not focus on interaction design for HUDs. According to Milicic (2010, pp. 77-78), when creating concepts for HUDs, one should avoid or minimise redundancies between instrument cluster and HUD. This could be done by displaying information only when it's needed and by the usage of fading in and out animations to gain better clarity of the displayed content. Further, developers should prevent overlaps of visual content shown in the HUD. Also, horizontal displacement should be avoided because fixed visual anchors support spatial memory. Animation should be used in a meaningful way to guide the driver's attention to important information or objects. In addition, the level of detail and size of displayed content should be reduced to decrease complexity. When it comes to the usage of text blocks in HUDs, developers should integrate them sparingly or use icons instead. Finally, one should decide well which and how many design elements should be integrated into the corresponding HUD concept.

Pfannmüller (2017, pp. 163-164) gives design recommendations that address AR HUD concept development in general, based on studies in the driving simulator and a prototype vehicle. A design recommendation for AR HUD in general is that one should avoid overlapping of AR content and real objects (cars, traffic signs, etc.) or reduce this to a minimum. One can minimise overlapping by just displaying the outlines of an AR content e.g. or by simply switching to a two-dimensional, non-contact analogue visualisation. Furthermore, the integration of shades in AR HUD concepts to support distance perception is not advised as it affects the visibility of elements in longer distances (Pfannmüller, 2017, p. 65). Additionally, the AR content should not be cut off, which can easily happen as the FOV of AR HUDs is limited. Also, one should be careful to not make the AR content too large or dominant. Besides, designers should be careful to not display too much content at the same time as this might overwhelm the driver. Pfannmüller (2017, pp. 163-164) mentions that only information that is relevant for the primary driving task should be displayed in the AR HUD and at the same time this content should only be shown when it's required. Further, animation should be used carefully because of its salience. This property could be used to guide the driver's attention to help him to recognise and react to obstacles on the road like other road users. Therefore, it is also essential that the displayed animation is easy to understand.

6 Concept Development Approaches for AR HUD

In this chapter, an expert evaluation, addressing AR HUD concept development approaches, is described with the aim of finding an optimal development solution which should help to facilitate and to accelerate the concept development process. First, two 3D projects for AR HUD concept design were created. The integrated use cases were *navigation*, *lane departure warning* (LDP), and *collision prevention assist* (CPA). In addition, this concept development approach was compared to another design method using real driving scenes. Based on the findings, an ideal concept development process for AR HUD was proposed and guidelines for improving the 3D tool approach were giving.

6.1 3D Tool for AR HUD Concept Development

For the expert evaluation presented in this section, two projects for the 3D tool *Cinema 4D* were created aiming to support designers while creating and comparing AR HUD concepts. The integrated use cases were navigation, LDP, and CPA. Furthermore, the developers tried to include various traffic situations, which are challenging to concept developers in the virtual 3D world. In the expert evaluation this concept development approach was compared to another design method based on the fusion of virtual 3D objects and real driving scenes. Based on the results, guidelines for improving and extending the 3D approach are summarised and an ideal concept development process for AR HUD is suggested.

6.1.1 Rapid Prototyping for AR HUD

To compare and evaluate design concepts for AR HUD, there is the possibility of conducting studies in a driving simulator as well as in the field. However, developers often do not have the possibility of conducting costly and time-consuming studies and need to find another way to test a large number of different concept variants.

In a study conducted by Israel (2013), three navigation variants for AR HUD were compared by showing concept videos to the participants: A tube, an arrow, and a so-called *virtual cable* as proposed by Grabowksi, Zamojdo, & Clegg (2011).

The aim was to find the most suitable one for a follow-up study in the driving simulator. The videos consisted of virtual navigation information and a real driving scene. The participants had to rate the concepts according to accuracy, distraction, and suitability as a navigation cue. After watching a video of each navigation variant, the tube was ranked as the most accurate one, whereas the arrow was assessed as the least distracting one.

Another efficient way to compare two different navigation concepts with four variants each, was described by Pfannmueller (2017). The experimental setup consisted of an AR HUD mock-up that represented a vehicle cockpit and a projection-screen in 10 meters distance (cf. Figure 10). The screen showed a video of a real traffic scene from the driver's perspective, which was displayed with a beamer. The AR content shown in the HUD was projected onto the driving scene while the participants were standing behind the AR HUD mock-up looking through the windshield. Unlike in a simulation or field study, the subjects could not interfere in the driving scenario.

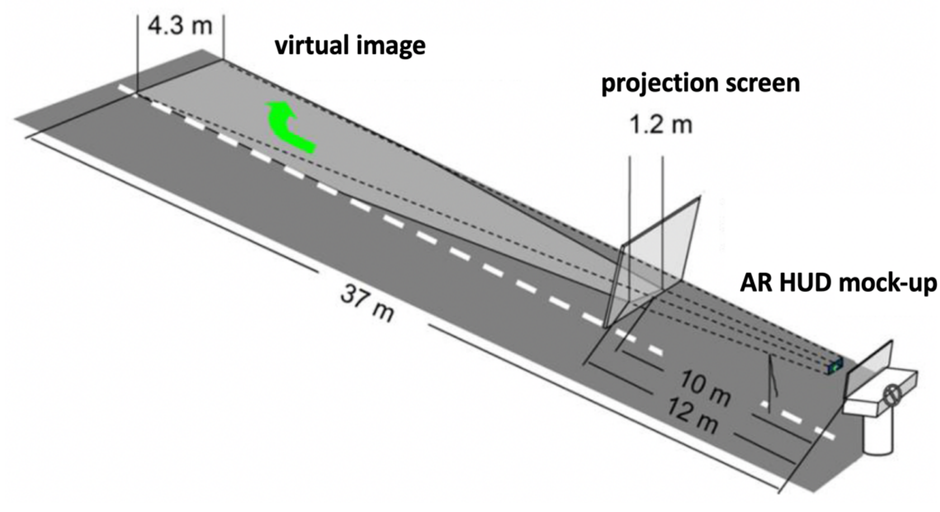


Figure 10: An example for an AR HUD mock-up (Pfannmueller, 2017).

Choi, Lee, Jung, Tayibnapis, & Kown (2018) present a simulation framework proposal for the visualisation of AR HUD concepts with an integrated homographic registration-algorithm that processes ADAS information. The purpose of this system is to minimise display errors caused by the difference between the view plane of driver and HUD. The presented simulation framework consists of three components. The first one is the driving simulation test bed that is responsible for the simulation of a real-world driving environment. The second component is the region-based inference model to process and visualise ADAS information. The third element is a homographic projection-based geometric registration-algorithm that forwards revised and improved recognition-information to the driver.

6.1.2 Use Cases

As the FOV of the AR HUD is very limited, one has to only select use cases that directly support the driver with his or her primary driving task and contribute to driving safety on a high level. This is recommended by Pfannmueller (2017) along with avoidance of large-surface representations of visual content in the HUD. Thus, the following use cases that support the driver with longitudinal and traversal control were chosen:

- *Navigation*: This use case was considered the most important one. The idea of showing information about route guidance in the driver's primary FOV has huge potential to reduce eyes-off-the-road times, especially in city scenarios with many manoeuvres in a short time.
- *Lane departure prevention* (LDP): Showing the driver visual signals in the HUD when the vehicle is drifting out of its lane, increases safety and thus, supports the driver with traversal control (VDI Wissensforum GmbH, 2019).
- *Collision prevention assist* (CPA): This system warns the driver in case the vehicle's speed is too high when approaching a car ahead. Showing visual information in the HUD supports the driver with longitudinal control (VDI Wissensforum GmbH, 2019).

6.1.3 Challenging Situations for Concept Designers

When developing concepts for an AR HUD, one has to make sure that visualisations work for all kinds of traffic situations and road profiles. With the help of focus groups with experts in the fields of AR, interaction design, and

HUDs, driving situations that are especially challenging for AR HUD concept developers have been chosen and are listed in the following:

- *Long bend*: Most of today's realisations of an AR HUD system in prototype vehicles come with a very limited FOV that is placed in the driver's primary FOV and can only be adjusted in y-direction to a certain degree. Further, the AR HUD shows visual content in a certain distance in front of the vehicle. The system developed by Continental AG (2019) e.g., uses a distance of 7.5 meters. Thus, in case of a long right or left bend in the road, most part of the FOV lies outside of the street making it impossible to show contact analogue information on the current stretch of road.
- *Roundabout*: A roundabout comes with a similar problem as long bends. Most of the time it is not possible to display contact analogue content on the street when driving through a roundabout due to the limited FOV. Thus, it's very difficult to display meaningful contact analogue information when the driver has to exit early enough so that there's enough time to react.
- *Crests and drops*: In case of a crests and drops the virtual content cannot be shown in the usual distance due to the steep incline of the road. When approaching the top of a crest, the FOV will lie above the street and consequently contact analogue information cannot be shown directly on the road anymore.
- *Fast sequence of manoeuvres*: When driving through a lot of curves in a short time, the FOV lies mostly offside the road. In this case, one has to think about an alternative visualisation. Overtaking another vehicle e.g. is a fast sequence of two manoeuvres as well.

- *Vehicle driving ahead*: The AR HUD developed by Continental AG (2019) shows virtual content 7.5 meters ahead of the driver. In case of a vehicle being directly in front of the own one, the shown contact analogue content should not be visible, otherwise this could lead to distraction. Concept developers need to compare different variants to find the best solution for this situation.

6.1.4 Cinema 4D

Cinema 4D is a complex and powerful 3D modelling application with integrated rendering function. It is possible to adapt certain parameters while showing a preview of the created scene, which makes it possible to change concept variants in real-time (Maxon Computer GmbH, 2019). With the programming-interface *XPresso,* we used a node-based visual scripting language included in *Cinema 4D,* which allows the developer to create automated interactions between various objects. This module supports 3D artists to generate animations. Furthermore, *Cinema 4D's* integrated programming or scripting language *C.O.F.F.E.* was used for parametric and generic modelling (Mamgain & Verghese, 2018).

6.1.5 3D Projects for Rapid Prototyping

In this section, common and separate features of the developed *Cinema 4D* prototypes for the use cases navigation and driving assistance are described (cf. *Research Question EE 1*).

6.1.5.1 Common Features of Both Prototypes

In the *object manager* section, which is part of every *Cinema 4D* project, the basic structure of the two *Cinema 4D* projects can be seen. The areas marked with an *edit tag* can be adapted by the user. Furthermore, the *object manager* contains various interfaces that represent predefined AR HUD concept variants with a pre-set of adjustable parameters related to the corresponding use case. If needed, the user can add new interfaces. To change the value of parameters, one has to click on the connected interface and select the tab *user data*. Each interface is connected with a related *XPresso tag* that contains required logic and is responsible for forwarding the corresponding parameter values to the scene's objects. With both 3D projects, the user is able to render concept videos in different formats. Figure 11 illustrates a screenshot of a generated video that contains an exemplary navigation concept design in the context of crossroads with traffic lights.

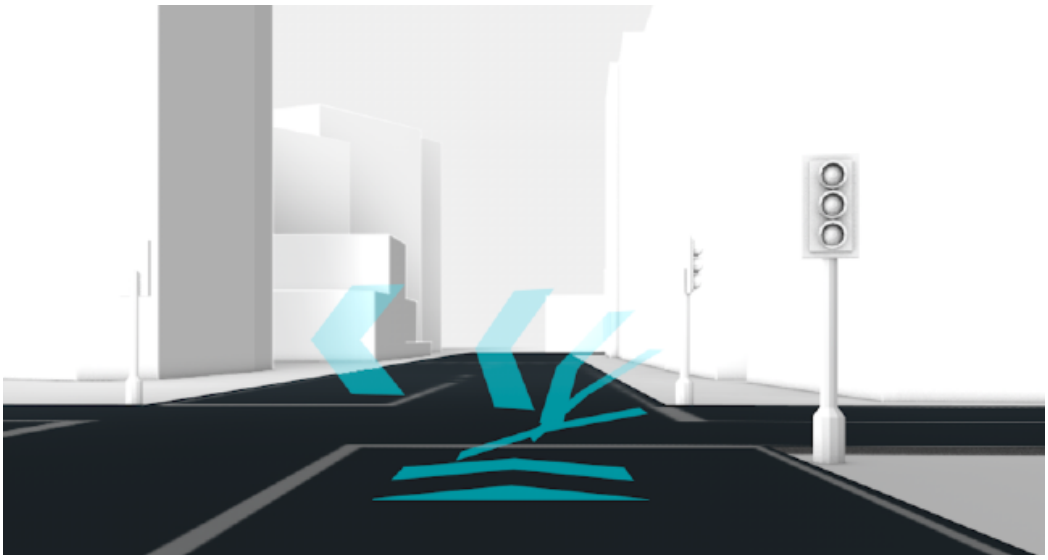


Figure 11: Screenshot of a rendered video created with the concept tool for Cinema 4D.

6.1.5.2 Prototype for the Use Case Navigation

In the first 3D project for *Cinema 4D*, design concepts for the use case navigation can be displayed, compared, modified, and evaluated. Figure 12 illustrates the structure of the created 3D project: At the top left, the user can see a view, which displays what the driver is seeing through the windshield of the vehicle together with the virtual information projected by the AR HUD. The window to the right contains a top view of the virtual city scene. At the bottom left side, a compilation of predefined *Cinema 4D* materials is provided, which can be assigned to concept elements and be extended with new ones. Hence, the user is able to quickly assign different colours and materials to the current navigation concept. At the top right, a selection of already implemented basic concept variants is given. Below this list, the tab *user data* is located, which includes parameters to adjust different attributes of each navigation concept. All of the integrated 3D objects have been modelled without the usage of textures. Thus, the performance is increased and also the time that it takes to render concept videos will be reduced.

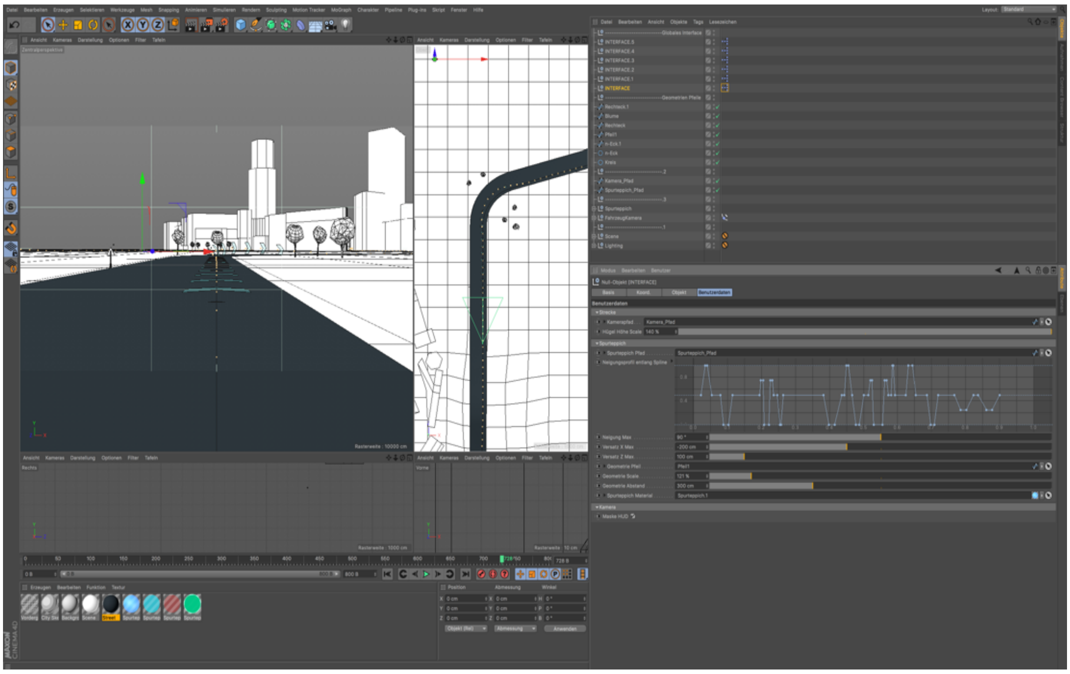


Figure 12: A screenshot of the 3D project for the use case navigation.

To adjust parameters in this project, the user has to click on the tab named *user data*. To adjust the navigation variants, one has to select the section *AR navigation*. The attribute *offset in x- and z-direction* represents the offset along the predefined path of the motorcar. The value *slope profile* describes the slope of the current navigation concept elements along the vehicle's path while influencing the *x*- and *z*-offset as well. Moreover, a value for the *maximum slope* can be determined. The geometry of the displayed virtual elements can be adapted in terms of the chosen basic object for the active navigation concept. The parameter *geometry scale* represents the geometry's distortion in the path-direction and the value *geometry distance* describes the gap between the single concept elements. Furthermore, the material of the displayed navigation hints can be adjusted by adding new ones or selecting a predefined one. Finally, the FOV of the HUD can be masked by clicking on a corresponding checkbox.

The integrated test track (cf. Figure 13) consists of two city scenes, which are connected by two road sections. In the left city, one can find basic left and right turn-off points, a crosswalk, and a roundabout with two lanes. One of the two roads that connects the cities, contains an obstacle standing on the street that needs to be driven around and various sharp curves. The second connecting road includes various sharp and long curves. Furthermore, the user can find a street segment that represents either a crest or a drop depending on how the user defines the corresponding height value. This value can be modified under the section named *track* in *user data*. The city on the right side represents a metropolis with densely built houses and skyscrapers. It also contains a crosswalk, a roundabout with a single lane, and an intersection with traffic lights.

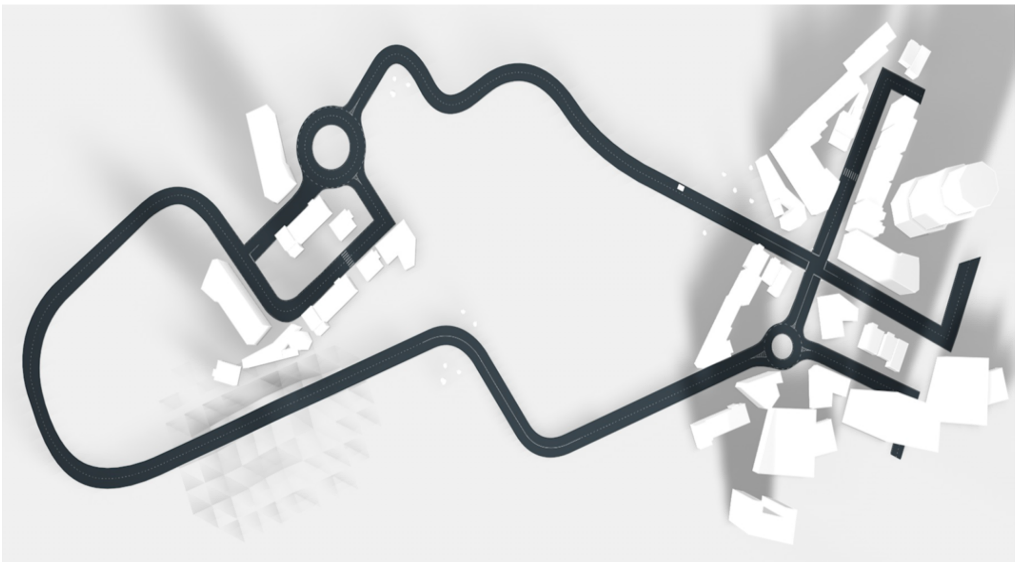


Figure 13: The test track of the Cinema 4D project for the use case navigation.

6.1.5.3 Prototype for the Driving Assistance Use Cases LDP and CPA

In the second 3D project, design concepts for the use cases LDP and CPA, which are part of the ADASs can be created and compared. The basic structure of this *Cinema 4D* project (cf. Figure 14) is similar to the project for the use case navigation, which is described in the section above.

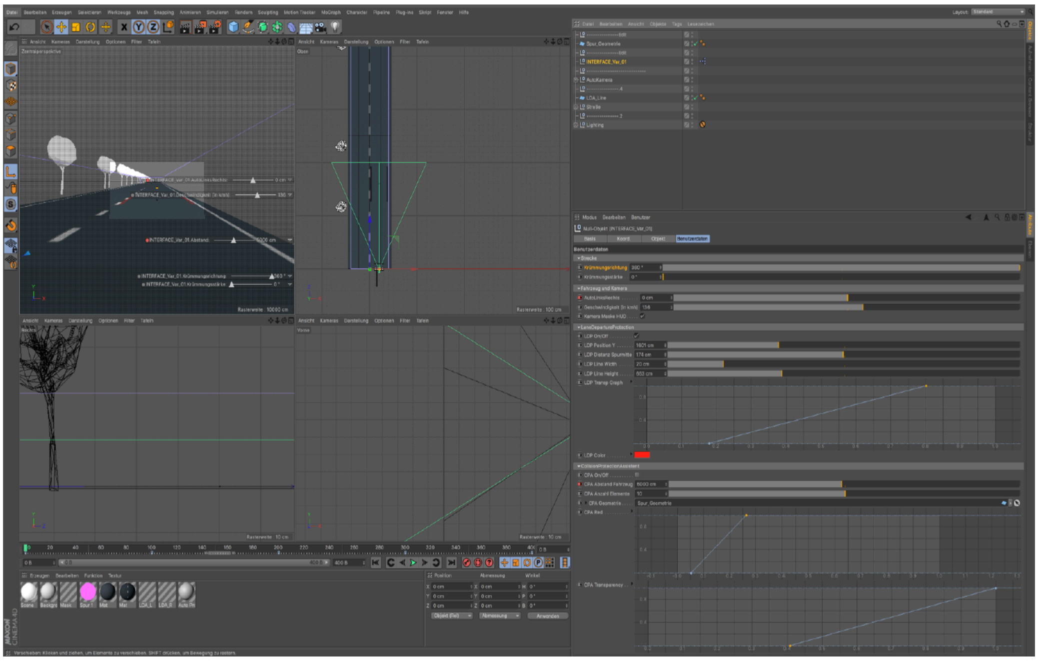


Figure 14: The Cinema 4D project for the ADASs use cases.

The attributes of the concepts can be accessed by selecting the corresponding interface in the *object manag*er section and by clicking on the tab *user data*. The virtual vehicle drives on a test route consisting of a section that is looped. The curvature of the road can be adjusted regarding strength and direction (cf. Figure 15). This can be done under the paragraph called *track*. Also, the determined values for the curvature refer to a length of 100 meters, which means that a bending of 180 degrees corresponds to a radius of around 16 meters. Hence, all possible kinds of curves can be considered and tested with this tool. This is mandatory in the development process of ADASs concepts as the generated variants need to work for a great amount of road types and situations.

Figure 15: Exemplary modifications of the test track of the Cinema 4D project for ADASs.

The paragraph named *vehicle and camera* includes three attributes: The first one, *car left/right*, describes the distance of the virtual camera and the centre of the lane. The second one, *vehicle speed (in km/h)*, represents the current speed of the virtual vehicle. Lastly, the user can choose whether virtual elements should be displayed outside of the HUD frame or not by clicking a checkbox. The shown virtual content representing the use case LDP, can be modified as well. The user can choose whether an LDP visualisation should be displayed and determine its distance to the position of the camera as well as to the centre of the lane. Furthermore, the values for width and height of the active LDP concept variant can be adjusted and the colour of the AR content can be selected. The attribute *LDP transp. graph.* comprises the relation between distance to the lane marking and the fade-in behaviour of the LDP. This behaviour is described with the help of a graph. The second use case for which the user can create concepts within this *Cinema 4D* project is called CPA. Again, one can choose whether to show the virtual content related to this use case or not. Further, the user can determine the distance between vehicle and CPA visualisation together with the car ahead and choose the number of objects the displayed concept variant consists of. The value

CPA geometry comprises the reference geometry and the attribute *CPA transparency* stands for the transparency of the concept objects. The parameter *CPA red* contains the distance at which the colour of the virtual information starts to turn red and the duration of how fast this happens. Moreover, it is possible to show both ADAS use cases at the same time. Figure 16 illustrates a combination of an LDP and CPA concept variant. Thus, concept developers can also investigate on how to visualise and combine multiple use cases at the same time.

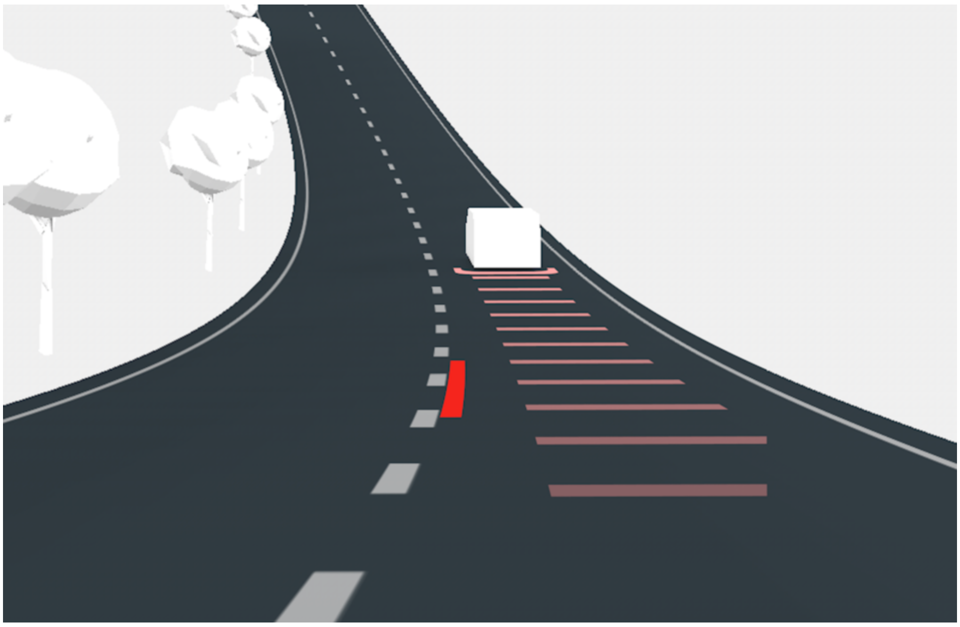


Figure 16: The adjustable test track of the Cinema 4D project for ADASs.

Furthermore, sliders for quick access to five different parameters (*car left/right, vehicle speed, distance to car ahead, curvature strength, and curvature direction)* are directly integrated in the perspective showing the driving scene.

6.2 Expert Evaluation of the 3D Projects

In this section, study design and results of an expert evaluation are described in which the concept development approach using a 3D tool was compared to an approach based on the fusion of virtual 3D objects and real driving scenes. Based on the findings, guidelines for improving the 3D approach are given and an ideal concept development process for AR HUD, together with a suitable toolchain, is suggested. All questionnaires that have been used in this study can be found in Appendix B.

This expert evaluation did not focus on improving the user experience or usability of the investigated 3D projects. This could be done in a follow-up study, in case the 3D tool approach is evaluated as meaningful tool for AR HUD developers. For this, researchers can conduct an expert review and look at user experience guidelines such as *The Eight Golden Rules of Interface Design* (cf. Shneiderman et al., 2016, pp. 74-75) or *The 10 Usability Heuristics for User Interface Design* (cf. Nielsen, 1994).

6.2.1 Participants

The participants of this expert evaluation were employees of *Daimler AG*, all working as concept developers for AR HUD. Further, each subject was knowledgeable about the topic user experience and was familiar with *Adobe After Effects* and at least one 3D modelling tool. In total, 6 experts took part in the evaluation of which 2 were female and 4 were male. The subjects ranged in age from 20 to 33 years with $M = 26.5$ and $SD = 5.82$. All participants graduated or were studying a subject in the fields of computer science or interaction design and were working as AR concept developers. Their experience in the area of interaction design in the automotive sector ranged from 11 to 72 months with $M = 31.82$ and $SD = 22.84$ while the experience in AR HUD concept development ranged from 2 to 60 months with $M = 17.5$ and $SD = 21.54$.

6.2.2 Procedure

First, participants had to fill a questionnaire covering demographical data, course of study, current job, and experience in the field of interaction design as well as AR HUD concept development. All questionnaires mentioned in this section are described in more detail under 6.2.3. Next, a persona (cf. Appendix B.2) was explained to the experts, so that they got an idea about the needs, goals, and problems of a typical user working with the presented tools for AR HUD concept development. This persona represents the experts that took part in the study. Next, both concept design approaches were shown and explained in a randomised order. First, the experts had to review the approaches for the topic driving assistance and next, for the use case navigation while filling questionnaires covering qualitative and quantitative measures. The reason for this order was the fact that the 3D project for the driving assistance use cases was less complex and thus, it was better suited to get to know this design approach.

In case of the approach with real driving scenes, only videos were shown to the experts, as the subjects were very familiar with the approach already. In case of the 3D tools, the examiner explained the basic structure and functions of the projects and after that, the experts had to complete several tasks. Furthermore, the subjects could explore the corresponding 3D tool as long as necessary.

After reviewing each concept development approach, the participants had to take part in a final survey, answering further questions dealing with possible improvements in the field of AR HUD concept development.

6.2.3 Questionnaires

<u>Questionnaire with Quantitative Measures</u>

In order to compare the experts' opinions concerning the evaluated design approaches connected to the use cases, a questionnaire consisting of five items that used a 7-point Likert scale. The participants had to decide to what extend they agree with the given statements, whereby the value 1 means *strongly disagree* and the value 7 stands for *strongly agree*. The first item was dealing with the suitability of the current approach for comparing concept variants in an effective way. The second statement addressed the process of getting decisions of managers in early concept development stages. Item number three was dealing with the evaluation of AR HUD concepts in different driving situations and item number four addressed the flexibility connected with the current design approach. In case of the fifth question, the experts had to rate the design approaches regarding their general suitability as AR HUD concept tool.

<u>Questionnaire with Qualitative Measures</u>

After reviewing each variant, the experts had to answer qualitative questions as well. In all cases, the subjects were asked what they like about the current approach and for what reason. Further, they had to state what they do not like about the approach together with giving an explanation for it. In case of reviewing the 3D tool for driving assistance, they also had to answer three additional questions dealing with content and functions that should be added or are unnecessary. Also, the subjects were asked about content that could be added to the predefined driving scene. In case of reviewing the 3D tool for navigation, the experts had to answer four additional questions. Again, they had to name functions that should be added or removed and what content should be added to the driving scene. Also, they had to suggest what basic navigation concepts could be added to the 3D tool.

Final Survey

After seeing all variants, the subjects had to fill a final survey consisting of two parts. The first part was made up of four open questions. In the first question, the five AR HUD use cases that are the greatest contributors to driving safety should be named without ranking. Next, the participants had to describe their ideal concept development process together with the necessary tools. Furthermore, the subjects had to state which parameters concerning weather and daytime would be a meaningful extension of the approach based on a 3D tool. Lastly, the participants were asked, whether they could name any country-specific traffic situations that could be added to the 3D projects. In the second part, the experts should rate seven different development tools that can be used for AR HUD concept design on a 7-point Likert scale from 1 (*not useful*) to 7 (*very useful*). Also, the participants should state when to use each tool in the development process.

6.2.4 Results

This section contains a compilation of the quantitative and qualitative results of the expert evaluation. The qualitative data was analysed, evaluated, and combined according to the *qualitative content analysis* by Mayring & Fenzl (2014), which is based on the inductive definition of categories.

Questionnaire with Quantitative Measures

After reviewing both development approaches for driving assistance and navigation, the experts had to answer a questionnaire consisting of five items using 7-point Likert scales whereby the value 1 means *strongly disagree* and the value 7 stands for *strongly agree*. The results for mean values together with standard deviations for the approaches for driving assistance are listed in Table 4 and the results for the approach for navigation are listed in Table 5.

Question	M (3D)	SD (3D)	M (RDS)	SD (RDS)
This approach is suitable for comparing concept variants in an effective way.	5.67	1.21	5.17	1.72
This approach supports concept developers process to reach a management decision early in the development process.	5	1.1	4.67	2.42
With the help of this approach, various driving situations can be evaluated effectively.	5.83	1.47	3.17	2.32
This approach provides full flexibility regarding the concept development process for AR HUD.	4.33	1.97	4.33	1.03
This approach is suitable for the development of AR HUD concepts.	5.83	1.17	5.33	0.82

Table 4: Results of the quantitative questions concerning the concept development approaches with a 3D project (3D) and real driving scenes (RDS) for driving assistance. Rating scales ranging from 1 (strongly disagree) to 7 (strongly agree).

Question	M (3D)	SD (3D)	M (RDS)	SD (RDS)
This approach is suitable for comparing concept variants in an effective way.	5.5	1.05	5.33	1.86
This approach supports concept developers process to reach a management decision early in the development process.	4.83	0.75	5.17	2.32
With the help of this approach, various driving situations can be evaluated effectively.	5.17	1.83	3.5	2.17
This approach provides full flexibility regarding the concept development process for AR HUD.	4.5	1.97	5.33	1.63
This approach is suitable for the development of AR HUD concepts.	5.33	0.52	4.83	1.33

Table 5: Results of the quantitative questions concerning the concept development approaches with a 3D project (3D) and real driving scenes (RDS) for navigation. Rating scales ranging from 1 (strongly disagree) to 7 (strongly agree).

Questionnaire with Qualitative Measures

After reviewing the concept development approaches for driving assistance and navigation, the experts had to answer a set of open questions. For both, 3D tool and real driving scenes, the subjects had to explain what they like about the idea and what they do not like.

For the real driving scenes in the context of driving assistance, two experts mentioned that they like the fact that users can quickly create high-quality concept visualisations. Two subjects stated that this approach comes with a high flexibility regarding concept design and further, it was mentioned two times that users recognise problems that they wouldn't see in a virtual environment. Lastly, it was mentioned one time each that this approach has a high degree of realism and that it is useful for management demos.

When it comes to things that the experts did not like about the approach, it was mentioned four times that the creation of real driving scenes costs a lot of effort in terms of tracking and recording videos. Further, two experts criticised that it is not possible to record a suitable video for every possible driving scenario.

It was also mentioned once that the real driving videos are only available in 2D and thus, are missing the effect of depth. Furthermore, experts criticised that subsequent changes are difficult to realise and that it is not possible to recycle created scenes (one vote each).

In case of the 3D tool with driving assistance use cases, two subjects each appreciated the control using the integrated sliders, the intuitive interface, and the fact that a quick adjustment of the included parameters is possible. One subject each liked the live-preview of the driving scene, the possibility to simulate critical traffic situations without anyone getting in danger, and the fact that 3D developers are already familiar with tools like *Cinema 4D*. Two subjects appreciated that the communication with developers gets facilitated by the integrated parameters as well as 3D models. One subject mentioned that the virtual driving scene can be adapted quickly. Also, it was mentioned one time that the comparison of similar concept variants is possible without a lot of effort.

When it comes to points of criticism regarding the 3D tool with driving assistance use cases, it was stated four times that the integration of completely new or different concepts could be difficult and time consuming. Further, it was mentioned one time each that the possibility to show or hide the integrated use cases is hard to find, that variable names are too long, and that the virtual scene is not realistic enough.

In case of the 3D tool with driving assistance use cases, the experts were also asked, which functions they would like to add to the development environment. Table 6 contains a summary of the given answers. Three experts wished for an extension of the included parameters, to be more flexible in the adjustment of concept and virtual driving scene. Three experts would include a possibility to switch between different degrees of realism concerning the virtual environment starting from fundamental objects to having a real driving video as background. Two experts each suggested to include a separate editor to create new concepts together with their behaviour and to include data from recorded signal files of real vehicles. Further, it was suggested once that hardware parameters of the HUD like projection distance and FOV size should be adjustable. Thus, different hardware variants could be considered and compared. The possibility to simulate inaccurate sensory data was mentioned once to get a more realistic concept behaviour and also, the integration of VR glasses was stated once. One subject suggested to add static content to the AR HUD, e.g. current vehicle speed, to investigate the interaction of contact-analogue and static elements. Lastly, one expert wished for the integration of further use cases.

Statement	Votes
Add more parameters	3
Switch between detail degrees of virtual world	3
Editor for AR HUD concept creation	2
Importing data of real vehicles	2
Adjustment of HUD parameters	1
Simulation of inaccurate sensory data	1
Integration of VR	1
Display static content	1
Integration of further use cases	1

Table 6: Content and functions that could be added to the 3D tool for driving assistance.

The next question the experts were asked after reviewing the 3D tool for driving assistance, addressed irrelevant content or functions of the introduced project. It was mentioned that the parameter names of sliders are too long and that the trees included in the driving scene are not necessary for the concept development process.

Lastly, the participants were asked about situations the current driving scene could be extended with. An overview is given in Table 7. It was mentioned two times each that traffic should be added and that the city scenarios should be extended with e.g. pedestrians or more types of buildings. Furthermore, two subjects suggested to add a motorway scenario together with motorway access and exit as well as a selectable amount of driving lanes. Further situations that the experts stated were LDP markers, special events like construction sites or road bumps, and a country road scenario with "spacious grasslands".

Statement	Votes
Integrate traffic	2
Extend the city scenarios	2
Integration of a motorway section	2
LDP markers	1
Special events (e.g. construction sites)	1
Country road section with "spacious grasslands"	1

Table 7: Situations the driving scene of the 3D tool for driving assistance could be extended with.

Also, in case of the use case navigation, the concept development approach based on real driving scenes was compared to the approach using a 3D tool.

When asked what they like about developing AR HUD concepts with the help of virtual elements mapped on real driving scenes, four experts appreciated the high degree of realism. Three experts stated that they like the high flexibility regarding concept visualisation that comes with this approach and two subjects mentioned that concept developers can see the influences of the real world immediately. Furthermore, it was said by one expert that real driving videos are suitable for management presentations due to their high degree of realism.

When asked what they do not like about this approach, five subjects mentioned that creating material with this method causes a lot of effort in terms of tracking or synchronising concept and video. Further, it was mentioned twice that the available video material is limited as it is not possible to cover all possible driving situations. One expert criticised that the real driving scenes might give the wrong impression regarding the progress of the concept due to looking too perfect. Thus, managers could think that the concept is already done, although it is still in early development stages. Lastly, one participant mentioned that the scenes cannot be recycled or adapted to create further concept variants.

After reviewing the 3D project for the use case navigation, the experts were also asked what they liked about this method and what not.

When asked for things they appreciated concerning this tool, two experts mentioned the possibility of creating driving scenes with various concept variants in a fast and effective way. Two subjects liked the possibility to adapt the included road situations and concept details. One expert each appreciated the extensive selection of integrated manoeuvres, the option to quickly switch between single concept variants, the minimalism of the 3D project, and the good suitability to generate wireframes. Further, one subject mentioned that the tool helps developers to evaluate first challenges regarding concept behaviour in demanding driving situations. Lastly, one expert liked that the concepts are available as a 3D model and thus, can be directly shared with developers.

When asked what they do not like regarding the 3D project, three experts mentioned the performance, which is not good enough at the moment. Two subjects criticised that the presented 3D environment is not realistic enough and two subjects said that the integration of entirely new concepts comes with a high effort. Also, it was mentioned that the track layout is confusing and that the handling of the tool is too complex (one vote each).

In case of the 3D project, the participants had to answer four additional questions. The first one addressed content and functions that should be added to the project. A summary is given in Table 8. Three experts suggested to make it possible to choose between different degrees of realism, up to a completely realistic background showing a video of the real-world environment. Two experts mentioned that they would add more parameters to adapt concepts and virtual world and two subjects suggested to include all navigation and driving assistance use cases into one tool. Also, one participant would like to have a loop function for certain road sections together with a possibility to directly select them. One expert missed a possibility to create own driving situations and another one explained that there should be a possibility to render background and AR content separately from each another. Next, it was suggested to integrate VR glasses to give a more realistic impression of the created concept variants and to add an interface to import signal data that has been recorded during test drives with a prototype car (one vote each). Lastly, one expert each suggested to integrate a possibility to simulate inaccurate sensory data like GPS or road map information and to provide a camera perspective that also shows the cockpit of the car together with e.g. instrument cluster and steering wheel.

Statement	Votes
Switch between different degrees of realism	3
Add more parameters	2
Integrate more use cases	2
Select and loop certain driving situations	1
Editor for constructing own driving situations	1
Separate rendering of background and AR content	1
Integrate VR	1
Read out parameters from signal data	1
Simulate inaccurate sensory data	1
Vehicle cockpit perspective	1

Table 8: Functions that should be added to the 3D project for navigation concept design.

Next, the experts were asked which content or functions are not necessary and can be removed from the 3D project. One participant said that the selection of basic shapes is not needed as concept developers would probably agree on a basic shape after short time. Another expert mentioned that the UI is too complex and should be reduced to a simpler version.

The next question addressed driving scenes that could be added to the 3D project. A summary of the results is shown in Table 9. In total, four experts suggested to add a motorway section with road access and exit. Three participants mentioned that they would add traffic including vehicles driving ahead of the own one or oncoming cars. Three experts said that they would like to investigate their concepts in manoeuvre situations with sharp angles like U-turns and two experts said that they are missing complex intersections. Further, it was suggested to add traffic signs like stop-signs, roundabouts in different sizes, crossing humans or animals, and an extension of the city scenarios by e.g. parking spots (one vote each). Lastly, it was mentioned that a section with country roads and wide “grasslands” would make sense and that LDP markings on streets are missing (one vote each).

Statement	Votes
Motorway with road access and exit	4
Traffic	3
Manoeuvres with a sharp angle	3
Complex intersections	2
Traffic signs	1
Roundabouts in different sizes	1
Crossing humans and animals	1
Extension of cities	1
Country roads with wide “grasslands”	1
LDP markers	1

Table 9: Functions that should be added to the 3D project for navigation concept design.

Finally, the experts explained which basic navigation concept behaviours could be added to the 3D project. Two participants suggested to integrate a basic concept behaviour that consists of an element that is directly placed at a fixed position in the real world and that can be animated towards or away from this location. Also, one expert wished for a basic concept behaviour consisting of an element that is fading in or out at a specific location but does not have to be world-fixed.

Final Survey

The final survey had two parts, whereby the first one consisted of four open questions.

First, the subjects were asked for their choice of the five most important use cases for AR HUD regarding driving safety. Table 10 shows a summary of the results, whereby only the use cases with at least two votes are listed here. The use cases mentioned most, with four votes each, are *navigation*, *collision prevention assist* (CPA), and *highly automated driving* (HAD). In case of HAD the experts mentioned that the driver's system trust could be dramatically increased by showing related information in the primary FOV. *Adaptive cruise control* (ACC) or *Distronic* (see Daimler AG, 2020) was mentioned three times while the variants with or without steering assist were put together. As four use cases got two votes each, it was not possible to determine the top five and thus, the list was extended with the use case brake distance, which shows the driver the remaining distance to a standstill in case of emergency braking. Further, the function pedestrian warning was mentioned, which should mark humans that suddenly cross the street. Also, the use cases *lane departure prevention* (LDP) and *traffic sign assist* (TSA) were named two times each. The TSA could support the driver by marking important traffic signs like speed limits or stop signs.

Use Case	Votes
Navigation	4
Highly Automated Driving (HAD)	4
Collision Prevention Assist (CPA)	4
Distronic (+ Steering Assist)	3
Braking Distance	2
Pedestrian Warning	2
Lane Departure Prevention (LDP)	2
Traffic Sign Assist (TSA)	2

Table 10: Meaningful use cases for AR HUD regarding driving safety.

The next question addressed the expert's ideal AR HUD concept development environment, together with the tools needed for it. For the very first phase in every concept development process, the brainstorming phase, two experts suggested to use stick-on notes and drawn sketches on paper. To visualise first concept designs, three experts suggested to create virtual driving scenes enriched with concepts, one participant suggested to combine real driving videos with virtual content, and one expert would use software tools like *Photoshop* or *Sketch*. Further, the participants wanted to work with real data and hardware as early as possible in the development process. Thus, two experts stated that it would make sense to combine concept simulation environments with real driving data and one expert suggested to play videos on the real HUD hardware to evaluate e.g. colour and contrast impressions. For certain use cases, it would be helpful to integrate them in a driving simulator to test them for all kinds of manoeuvres, according to one expert. To have an even more realistic experience, the integration of VR would make sense. Three participants mentioned that developed concept designs have to be tested with a prototype or series vehicle in real traffic. When a final concept is forwarded to software developers, the submission should contain images, videos, and 3D models, together with a detailed description according to three experts. Finally, to make sure that the developed AR HUD concepts are working as expected and do not bring any security risks with them, one participant said that field studies with real costumers should be conducted.

Next, the experts had to state which parameters concerning weather conditions and daytime should be included in a revised development tool. It was mentioned two times each that the simulation of fog, wet road, and snow would make sense. However, two experts were the opinion that weather conditions should be rather tested in a real-world environment as the degree of realism will not be sufficient when simulating them in a virtual world. Further, the integration of cloudy sky and bright sunlight was stated one time each. Regarding daytime, three experts suggested to add a function that could toggle between a day and night view. Two experts even wanted to have a more accurate way of determining the daytime together with the related lightning conditions. One expert suggested to offer shortcuts to choose predefined conditions like twilight, autumn day, midday sun, and night ride. Lastly, it was mentioned one time to make the angle of the sun configurable.

In the last question of the final survey's first part, participants were asked which country-specific road situations could be a meaningful extension to the 3D tools. Four experts suggested to integrate the simulation of left-hand traffic and two experts said that they would add a Michigan left. Further, one participant suggested to include a *high occupancy vehicle* (HOV) lane, which should encourage people to share their car in the USA and Canada. Lastly, one expert suggested to add country-specific sets of traffic signs for Europe, Asia, and North America.

In the second part of the final survey, the participants had to assess a variety of development tools regarding their suitability for AR HUD concept design. Table 11 shows the results together with the corresponding rank.

Rank	Development Tool	M	SD
1	*Virtual Reality*	6.33	0.75
2	*High End Driving Simulator*	6.33	0.75
3	*Sketch on Paper*	6.17	0.82
4	*Image Editing Tool*	5.67	2.4
5	*AR Glasses*	4.5	2.29
6	*Basic Driving Simulator*	3.5	2.32
7	*Table Top Stand*	3.5	2.14

Table 11: Assessment of the development tools for AR HUD use cases.

Furthermore, the experts were asked, in which phase of the AR HUD concept development an application of the single development tools would make sense. Table 12 shows a compilation of the suggestions given, together with the frequency of being mentioned. In this section, only the suggestions given at least two times are mentioned while a complete list can be found in the Digital Appendix.

Development Tool	Application
Virtual Reality	Communicate ideas and demos (2)
High End Driving Simulator	User studies (2) Concept validation (2)
Sketch on Paper	First ideas and concept designs (4) In every concept development phase (2)
Image Editing Tool	First ideas and concept designs (3)
AR Glasses	-
Basic Driving Simulator	Early and realistic testing of use cases (2) Not worth the high effort (2)
Table Top Stand	Too cumbersome (2)

Table 12: Application of development tools regarding AR HUD concept development.

6.2.5 Discussion and Conclusion

In this expert evaluation, two AR HUD concept development approaches for the use cases navigation and driving assistance (LDP and CPA) were examined. The approaches were concept development with the help of real driving scenes or suitable 3D projects (cf. *Research Question EE 2*). This section contains a compilation and interpretation of the findings.

The quantitative measures clearly showed that the great advantage of the 3D project approach over the real driving scene is the possibility to quickly and effectively compare concept variants in different driving scenes. In case of the real driving scenes, concept variants have to be integrated in a new video every time. At the same time, the video material is limited and it is impossible to cover all relevant driving scenes that way. For all other items, both approaches were rated quite similarly (cf. *Research Question EE 3*).

In the qualitative data section, the experts gave positive and negative feedback for both approaches.

In case of the real driving scenes, the participants appreciated the high degree of realism together with the suitability for management demos. Also, the full flexibility for concept development was highlighted as positive a couple of times. Furthermore, the experts mentioned that developers discover challenges and problems they wouldn't have found when solely creating a concept in a virtual environment. One of the main areas of concern was the fact that creating real driving scenes with integrated AR HUD concepts is very time consuming. Among others, concept developers need to track the video material and adapt each concept for exactly this scene. At the same time, the available videos are limited and it is not possible to provide examples for every scene. This problem has already been an outcome in the quantitative section. In addition, it is very difficult to reuse previously created video scenes, also if the video required next should be quite similar to the previous one.

In case of concept development with 3D projects, the experts appreciated the possibility to quickly create concept videos with similar concept variants, as already created scenes can easily be adapted and reused afterwards. Furthermore, it was mentioned that details of virtual driving scenes can be changed quickly and that developers can easily compare single concept variants by switching between them with only one click. Another big advantage of the 3D projects is that created concepts are directly available as 3D objects together with all integrated dimensions, measurements, and parameters. A main point of criticism was the high effort needed to integrate a completely new concept idea in the 3D project. According to the experts, similar concept variants could be created quite easily, but integrating a new concept with completely different animations, behaviour, and basic shapes could be challenging. Further, it was mentioned that the degree of realism of the virtual scenes is not high enough, especially when presenting the concepts to the management and that the performance in case of the project for navigation could be better.

For further improving the presented 3D projects for navigation and driving assistance (cf. *Research Question EE 4*), additional questions were asked to the experts. The first one addressed content or functions that should be added.

Among others, experts wanted to have a possibility to switch between different degrees of realism. Examples could be an entirely realistic visualisation suitable for demos and a very basic visual environment with only basic shapes to reduce rendering times and improve performance. Further, experts had the wish to integrate all use cases for navigation and driving assistance into one 3D project, to examine them interacting with each other. Also, it was suggested to integrate the possibility of connecting VR glasses to increase the degree of realism further. Next, participants mentioned that reading data from real sensory files would make sense. Some elements of the virtual world could be directly modified according to those parameters and values. Finally, the suggestion was made to simulate inaccurate sensory and GPS data, as you find them in actual vehicles and systems to make the behaviour of the developed concept variants more realistic.

Regarding the simulation of different weather conditions in the 3D project, the majority stated that theses could not be reproduced in a realistic fashion. These effects should rather be examined in the real world, together with a real AR HUD system. Regarding the simulation of different light conditions, it was suggested to integrate the possibility to switch between different pre-sets like day and night time. Also, it was mentioned to add a function for changing the current intensity of illumination.

Concerning expansions of the virtual traffic scene, it would make sense to add traffic, like other vehicles, cyclists, or pedestrians to e.g. cover challenges related to masking or collision of AR content with objects of the real-world environment. Also, a motorway section should be included together with access and exit, as the connected driving manoeuvres are required quite often and might require their own concept visualisations. Another driving situation that is a challenge for AR HUD concept developers is the turnaround or U-turn. Finally, experts suggested to expand the virtual cities in general by adding things like parking spaces, construction sites, and crossing animals or pedestrians. Thus, safety-critical situations can be simulated in a city scenario. Furthermore, the virtual driving scene could be enhanced with country-specific elements or situations to examine concept variants for different countries. Experts asked e.g. for an integration of left-hand traffic, a Michigan left, and country-specific traffic sign sets.

In case of the use case navigation, the participants were asked which basic concept behaviour or design could be added to the 3D project. It was suggested to integrate a display that is positioned in the virtual environment in a contact analogue way and can animate towards and away from this location. Another concept idea that was mentioned, is a concept fading in and out without having any fixed reference to the surrounding world.

Next, all suggestions for improvement given by the experts were analysed and classified in terms of effort needed for integrating them in the 3D projects available. The goal was to find suggestions that can be integrated quickly. This was done with the help of focus groups with employees of *Daimler AG*, experienced with the 3D tools *Cinema 4D* and *Blender*. Concerning the suggestion to integrate further use cases, only such ones with usually low complexity regarding design possibilities can be added quickly, e.g. *blind spot monitoring* (BSM) or static displays. The simulation of inaccurate sensory data could be realised with different self-created datasets. Furthermore, there are many features that can be added to the virtual driving scene without big effort, like the integration of traffic, a motorway section, or a turnaround. Also, the city scenes can be extended with additional buildings, traffic signs, or traffic lights quite easily. Concerning country specific extensions of the virtual world, the addition of a Michigan turn or country specific road signs could be realised in a short time.

Also, the experts were asked which AR HUD use cases they consider to be the most relevant regarding the enhancement of driving security. The findings showed that solely use cases from the fields of routing (e.g. navigation and HAD) and driving assistance (e.g. CPA) were mentioned.

Another aim of this expert evaluation was to collect ideas for an ideal concept development process for AR HUD together with the necessary tools (cf. *Research Question EE 5*). Figure 17 shows the developed process, which consists of five phases. In every phase it's possible and sometimes necessary to go back to the previous one.

During the first phase, concept developers brainstorm and collect first ideas with the help of post-it notes and sketches on paper. During the second phase, first concept visualisations are created with an image-editing software like *Photoshop*, *Illustrator*, or *Sketch*. Further, a 3D project like the ones examined in this expert evaluation is used to compare different variants of single concept ideas. For first presentations to team members or the management, real driving videos with integrated AR HUD concepts are used. In the third phase, the developed concepts have already reached a certain maturity. Thus, it is important to evaluate their robustness and to use examination methods that are closer to the series system. One way to do so, is to connect the 3D projects with VR glasses to simulate a virtual traffic scenario and to feel like a driver. To get a first impression of colour and display quality, concept variants can be tested on an actual HUD hardware in the laboratory. Also, first concept designs can already be integrated in a prototype car to test them in the real traffic with actual sensory data and HUD hardware. During the fourth phase, the concept will be evaluated. Ideally, this will be done in a prototype car in real traffic with a close-to-production AR HUD system. When there is no vehicle available, concepts can be examined in a high end driving simulator, like the one described by Daimler AG (2019). In the fifth and final development phase, the concepts will be submitted including concept pictures, videos, 3D models, and textual descriptions.

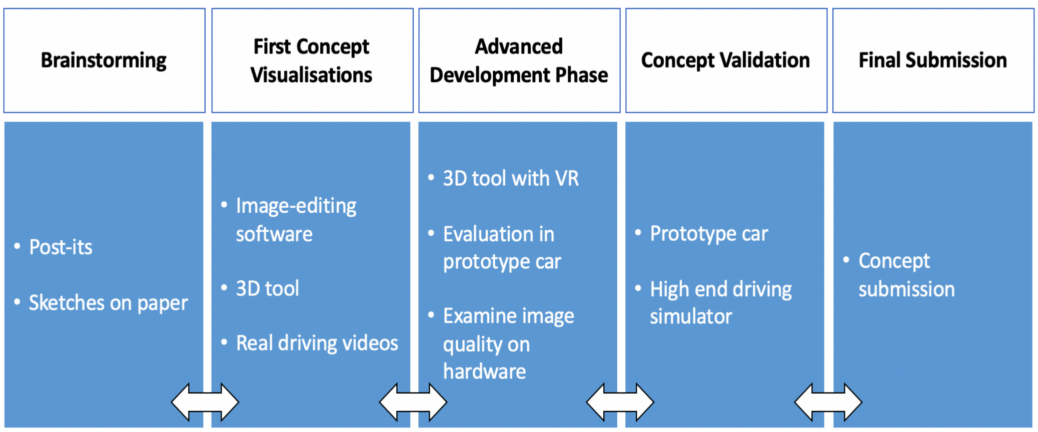


Figure 17: Exemplary concept development process for AR HUD.

There are limitations of this experiment that have to be mentioned. First of all, the participants were already familiar with the approach using real driving scenes while they never worked with the 3D tool approach. This circumstance might have influenced their assessment. However, all of the participants were experts in this field so they were able to work with the new approach in a short amount of time. Furthermore, the presented 3D projects were still in prototype phase and might have been rated even better if they had been finished products.

7 The Development of a Navigation Concept for AR HUD

This chapter contains the development of a navigation concept for AR HUD based on three different studies conducted in real traffic. All of the field studies were carried out in real traffic using a prototype vehicle that contained a complete AR HUD testing environment.

For the first field study, two similar variants of a pure contact analogue navigation concept for AR HUD were developed. The goals of this first field study were to find ways to reduce masking effects without reducing or impairing the displayed navigation information and to gather expert knowledge regarding AR HUD concept development. In the following study, a revised navigation concept was created based on the results of the previous study and was compared to one of its concepts. Thus, the investigators wanted to make sure that the revised version of the concept provides an added value to the driver compared to the previous one. Finally, the improved concept was compared to static HUD navigation as it is already available in today's series cars. The aim of this study was to evaluate how the new AR HUD technology compares to a similar and already known navigation approach.

7.1 Field Study 1: A Study to Collect Expert Knowledge for the Design of AR HUD Navigation Concepts

In this section, a field study in real traffic with a prototype vehicle is reported. The experiment served to comparatively examine two contact analogue navigation concept variants for AR HUD together with masking effects caused by virtual content during driving. Although T. Ross et al. (1996) recommend to use visual together with auditive information for DAS there was no audio output included in the study. The goal was to solely focus on content shown in the AR HUD. Displaying navigation cues is a meaningful and obvious use case for an AR HUD and is, according to Plavsic, Bubb, Duschl, Tönnis, & Klinker (2009), especially helpful in challenging and complex driving situations. The great advantage over conventional navigation systems is the localisation of the navigation cues in the driver's primary FOV. This can be achieved with a conventional HUD as well, but the human still has to assign the virtual information to the actual manoeuvre point which is not necessary when using an AR HUD. To collect valuable expert knowledge for the *topic navigation concept design for AR HUDs*, only experts in fields related to AR HUD development took part in this experiment. In total, 26 participants drove a predefined test track twice, in randomised order, to compare both navigation concepts and had to fill various questionnaires and answer open questions after each drive. Further information concerning the current state of related research, hypotheses, methodology, and results of the study are described in the following or in Schneider et al. (2019b, 2019a).

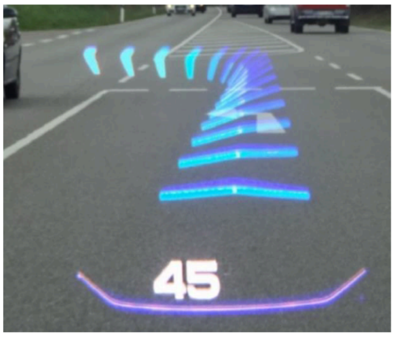
7.1.1 Current Research on Contact Analogue Navigation Concepts

There are general guidelines for HMI design and for the presentation of visual information in vehicles (e.g. Commission of the European Communities, 2008; International Organization for Standardization, 2017b; T. Ross et al., 1996). Studies addressing the design of AR HUD concepts have been conducted as well. In this section, we summarise and discuss a selection of these works with focus on the design of navigation concepts for AR HUD. Table 13 shows an overview of the AR HUD concepts discussed in this section together with the corresponding literature.

Schneid (2009, p. 89)

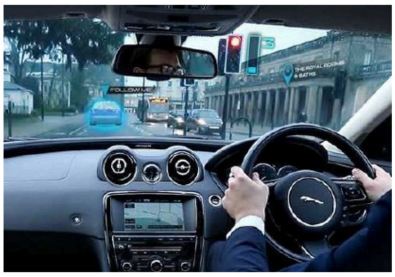
Grabowksi et al. (2011)


Israel (2013, p. 90)



Pfannmueller (2017, p. 135)

Bolton et al. (2015)


Jaguar (2014)


Tönnis et al. (2008)

Kim & Dey (2016)

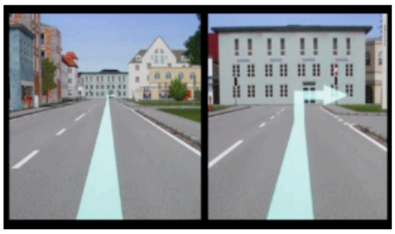

Bauerfeind et al. (2019)

Table 13: An overview of various concept design approaches for AR HUD navigation.

Schneid (2009, pp. 88-89) implemented a contact analogue navigation concept in a prototype car that had the shape of a green arrow which points into the direction of the upcoming manoeuvre point. Figure 18 shows an example of the navigation concept. The virtual element is located directly at the turn-off point and looks like an arrow that is painted directly onto the road. For larger distances (> 70m) the visual content will not get smaller anymore as this would lead to difficulties in terms of recognition and interpretation of the shown navigation hint. This concept was evaluated in an in-the-wild on-road study to increase ecological validity. In this study, the idea of a contact analogue navigation aid was assessed as positive by the majority of the subjects. One of the things the participants did not like was the poor perceptibility of the used concept colour which was *green*. To solve this issue, one could either use a different colour with higher contrast to the real environment or increase the brightness of the HUD's PGU. Further, the suggestion of using a different core element for the navigation concept with the shape of a tube was stated (Schneid, 2009, pp. 109-110).

Figure 18: A contact analogue navigation arrow by Schneid (2009, p. 89).

Another study, examining three very different navigation concepts for an AR HUD, was conducted by Israel (2013) to find a basic direction for the further development of a contact analogue navigation aid. The compared concepts were an arrow that is shown at the turn-off point, a tube that shows the trajectory the driver has to follow, and a so-called *virtual cable* (Grabowksi et al., 2011) that resembles a tram power line (cf. Figure 19). The subjects had to rate the concepts according to accuracy, distraction, and suitability as a navigation hint. After showing a video of each concept, the *virtual cable* was rated as unfavourable as the participants stated that it is unsuitable, inaccurate, and distracting. The reason for that could be the distance between cable and roadway that makes it difficult to connect those to areas and leads to a higher amount of glance aversion. Furthermore, the participants rated both, the arrow and the tube as suitable for contact analogue navigation. The arrow was interpreted as the less distracting concept, whereas the tube was assessed as the most accurate one. For future studies in real traffic, the arrow was chosen as the core element of navigation concepts. Enhancing the security by less distraction was more important than the accuracy.

Figure 19: The virtual cable (Grabowksi et al., 2011).

Next, Israel (2013, pp. 85-100) compared the resulting contact analogue navigation aid (cf. Figure 20) with a conventional one in a simulation study. Both navigation aids were displayed via a separate projector onto the virtual driving scene to simulate a HUD. The results showed that subjects made significantly fewer navigation errors with the contact analogue navigation aid. Also, it was shown that the driver's cognitive activity is lower while navigating with the contact analogue variant which was evaluated with the *Index of Cognitive Activity* (ICA) (cf. Marshall, 2002). For the assessment of the driver's workload, the unweighted NASA TLX OWI questionnaire was used. No significant difference between contact analogue and static navigation could be found. Additionally, Israel (2013, pp. 97-100) could show that the contact analogue navigation causes significantly less distraction by directly asking the subjects while there was no significant difference between these navigation concepts in terms of masking. Finally, the participants rated the contact analogue navigation better than the static one.

Figure 20: A contact analogue navigation aid with an arrow as core element (Israel, 2013, p. 90).

Pfannmueller (2017, pp. 164-165) developed concept design recommendations for the use case *navigation* in AR HUDs. Among others, the advice to include a two-dimensional preview of the upcoming manoeuvre is given. This could help especially when the position of the displayed AR content is inaccurate or when the viewing conditions are poor. Another advice is to show the driver the way with the help of a *fishbone*. This boomerang-shaped navigation concept should be preferred to an arrow or a conventional trajectory. While it is also recognised as a trajectory due to the effect of the *Gestalt laws of perceptual organisation*, the fishbone concept reduces the overlapping of objects in the real world.

Furthermore, Pfannmueller (2017, pp. 131-158) compared a conventional navigation system for HUD that is ready for series production to an AR HUD navigation system in a field study in real traffic. For this experiment, a within-subjects design was used to collect subjective assessments (e.g. functionality, design, usability, potentials, and weaknesses) and measure navigation errors as well as subjective workload. The aim of this experiment was to gain further knowledge concerning the design of navigation concepts for AR HUD and validate as well as extend the results of simulation studies. The contact analogue navigation concept consisted of an array of fishbones that were shown to the driver at the corresponding manoeuvre point (cf. Figure 21). The findings showed that the conventional navigation hints were rated as more pleasant than the contact analogue ones. Also, the positioning accuracy in the AR HUD was assessed negatively. Further, subjects rated the contact analogue display as less intuitive than the conventional one. However, subjects made less navigation errors while using the AR HUD navigation and no significant differences were found concerning the mental workload perceived by the drivers. Thus, developers of AR HUD concepts can be confident that, with further improvements, the contact analogue navigation can be a meaningful advancement of navigation systems in vehicles.

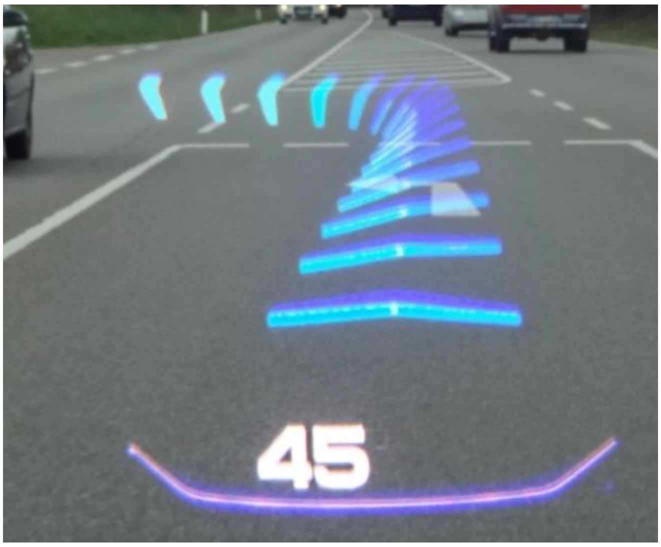


Figure 21: A contact analogue navigation cue suggested by Pfannmueller (2017, p. 135).

In a simulation study, Bolton, Burnett, & Large (2015) investigated the usage of landmark-based navigation in HUDs. The idea was to highlight the presented landmarks with AR to make them easier to recognise for drivers. In a driving simulator, different navigation variants were shown to the participants as either conventional distance-to-turn hints, contact analogue arrows on the road, or augmented landmark instructions as arrow or box. A compilation of the navigation concepts used is illustrated in Figure 22. When using the landmark realised as a box, drivers showed significant performance improvements regarding response times and success rates compared to the traditional distance-to-turn navigation. At the same time, the participants' workload decreased while navigating with this landmark variant. Thus, Bolton et al. (2015) concluded that landmarks presented with AR, provide significant benefits for HUD navigation systems.

Figure 22: Navigation concepts used for the experiment (Bolton et al., 2015).

As part of *360 Virtual Urban Windscreen,* Jaguar (2014) describes the idea of integrating a virtual *ghost car* that looks like driving right in front of the own motorcar to support the driver while navigating in busy urban scenarios. The driver can follow a virtual vehicle that is projected on the windshield. Figure 23 illustrates the corresponding idea. Also, Topliss, Pampel, Burnett, Skrypchuk, & Hare (2018) describe the idea of using a virtual lead vehicle to support AR navigation systems. Concerning the role of a lead vehicle, they found out that it could be useful at a range of different junction types but not in situations where a preview of the following steps or the overall situation is required. In a simulation study, Topliss et al. (2018) evaluated whether a virtual vehicle can support drivers in traffic situations with complex junctions, especially multi-exit roundabouts. They found out that the navigation and driving performance while using the virtual car concept was comparable with using a traditional screen-fixed variant. For that reason, the authors conclude that a virtual lead vehicle could be beneficial within AR HUD navigation systems.

Figure 23: The Follow-Me Ghost Car Navigation (Jaguar, 2014).

Tönnis, Klein, & Klinker (2008) investigated the perception and interpretability of AR content shown in larger distances in a driving simulator. Therefore, three different arrow-based concept variants for navigation systems (cf. Figure 24) were developed and compared. The findings showed that the perception gets affected more negatively in case of the flat arrow scheme than when using the other two variants. Also, it could be shown that rounded shapes reduce perception in larger distances. Regarding subjective mental workload, it could not be shown any difference between the three concept variants.

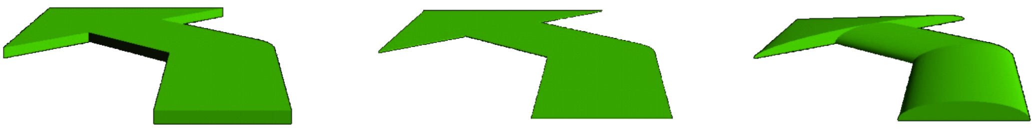


Figure 24: Left: Solid with hard corners - Middle: Flat arrow – Right: Solid with rounded shape (Tönnis et al., 2008).

In a driving simulation study, Kim & Dey (2016) examined visual distraction by comparing an AR HUD that displayed a virtual road extension (cf. Figure 25) to a conventional map display. While the map device required the participants to avert their eyes from the road and thus, interfered with the driving task, the virtual content projected in the upper windshield led to driver distraction by masking other traffic participants and the real-world environment.

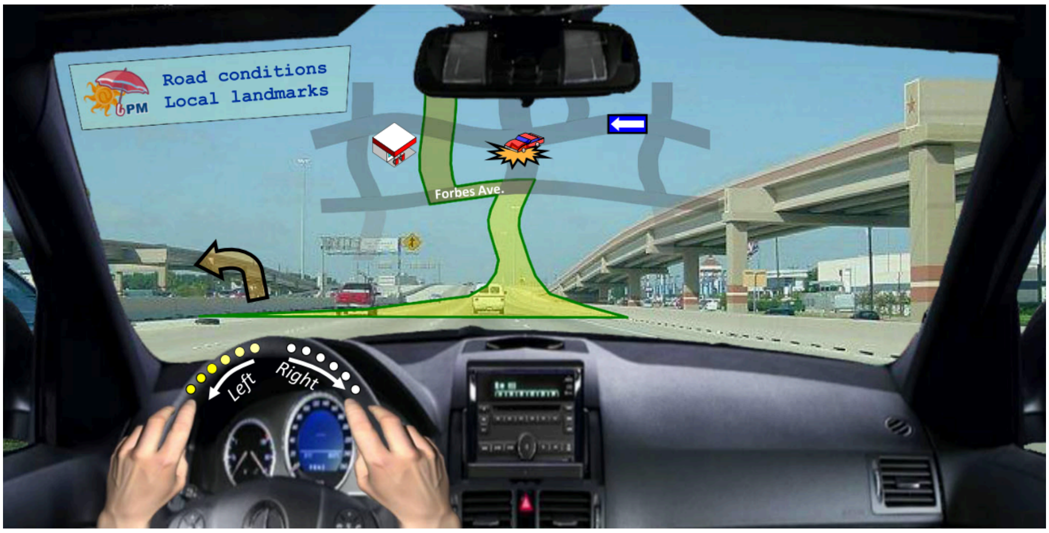


Figure 25: A windshield-based AR navigation display proposed by Kim & Dey (2016).

In a study conducted in a driving simulator, Bauerfeind, Drüke, Bendewald, & Baumann (2019) aimed to investigate the acceptance and effectiveness of an AR HUD navigation compared to a static one (cf. Figure 26). The results of the experiment showed that especially in ambiguous driving situations the AR technology gives the driver a better orientation. While navigating with the AR navigation variant, participants made fewer navigation errors and recognised the correct turn-off points or destination streets significantly earlier compared to the conventional HUD. Furthermore, the drivers rated the AR HUD as "more useful" and stated that driving with the AR display reduced their mental load while navigating.

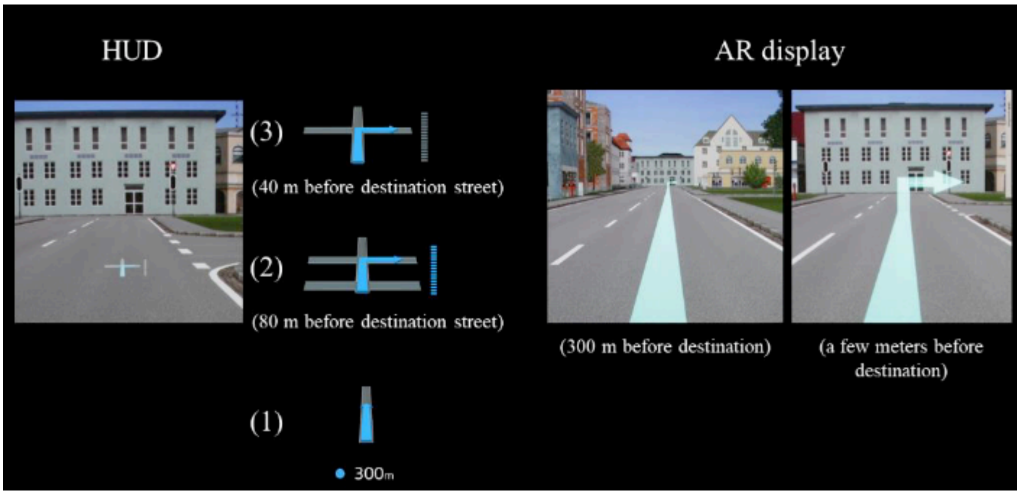


Figure 26: Left: A current version of a HUD developed by AUDI - Right: A contact analogue navigation variant (Bauerfeind et al., 2019).

7.1.2 Current Research and Problems with Masking

Displaying virtual elements in the driver's primary FOV is associated with a number of risks. Among them is the risk of masking other traffic events or road users (Gish & Staplin, 1995). This danger exists in the HUD particularly when a high amount of visual content is displayed or in case of a high information density (Yeh, Merlo, Wickens, & Brandenburg, 2003; Yeh & Wickens, 2001). The corresponding salience can lead to an unintended directing of attention towards the virtual elements which might result in overlooking safety critical situations in traffic (Atchley et al., 1997). Additionally, a violation of the monocular depth cue *occultation* can lead to confusion and ambiguity (Furmanski, Azuma, & Daily, 2002). This happens when virtual content is being projected in front of a real object, whereas it should be behind it. In a field study conducted by Schneid (2009), subjects criticised the collision of contact analogue navigation hints and real objects. Schneid (2009) suggested that the increase of the virtual elements' opacity could be a solution.

Pfannmüller (2017, pp. 63-66) examined whether the overlapping of visual content and a vehicle ahead has an influence on depth perception in case of AR HUDs with standing or lying virtual image plane. The study was conducted in a stationary prototype car. The findings showed that a collision of virtual and real objects leads to an underestimation of the distance of the virtual image for both cases. The experiment also indicated that in case of the variant with the lying plane, participants had a higher workload when the visual content was colliding with a real object. According to Pfannmüller (2017, pp. 63-66), this could be caused by the contradictory virtual content which could have a negative impact on the contact analogue effect. The experiment demonstrated that it is important to avoid masking caused by AR virtual content and two possible solutions were stated: In case of a detected collision of virtual and real objects, 2D or conventional content could be shown instead. Another solution could be to switch to a display mode where only outlines of the AR objects are shown (Livingston et al., 2003). In a further study in which AR HUD navigation cues were examined in a driving simulator, Pfannmüller (2017, pp. 128-130) demonstrated that an arrow with the shape of a fishbone was rated higher in terms of intuitiveness, clarity, and required amount of concentration, compared to a solid tube. The reason for this was that the fishbone shape covers less potentially relevant objects.

7.1.3 Concepts

Based on guidelines from research, especially the design recommendations from Pfannmüller (2017), Milicic (2010), and focus groups with experts in the fields of interaction design as well as AR (all employees of *Daimler AG*), two similar navigation concepts for AR HUD have been designed. As recommended by (Schneid, 2009), a colour with a high contrast to the real-world environment was chosen for both navigation concepts examined in this study: Light blue with the colour code *RGB (102, 153, 230)* and a transparency level of 0.

7.1.3.1 Solid Fishbone Concept

The first navigation concept, named *solid fishbone concept*, consists of three elements that are called *entry marker*, *middle marker*, and *exit marker*. All components do have the shape of a fishbone as recommended by e.g. Pfannmüller (2017) and Israel (2013), to achieve less masking of the real-world environment as well as a smoother cut when leaving the FOV. The idea of using landmarks as core elements as suggested by Bolton et al. (2015) was not further pursued due to the small size of the FOV of today's AR HUD systems and the often-imprecise positioning caused by inaccurate sensory and road map data. Also, a virtual car has not been included for traffic situations with complex junctions, as recommended by Topliss et al. (2018), because the concept should not be confusing which could happen by switching concept and visualisation types.

The behaviour of the three concept elements is as follows: When the driver approaches a manoeuvre point, the *entry marker* fades in first. The *entry marker* is a curved fishbone that is placed on the street in a contact analogue way and shows the upcoming turn-off direction (cf. Figure 27a). The *entry marker* disappears as soon as it would be cut off by the FOV of the AR HUD. The fade in and out time is 0.5 seconds for all elements of the *solid fishbone concept*. Next, the so-called *middle marker* fades in which is represented by a wall made of a fishbone standing on the edge. The element is placed at the centre lane of the street in which the upcoming manoeuvre points into (cf. Figure 27b). The *middle marker* is longer than the FOV so that it does not disappear while turning off (cf. Figure 27c). Directly after turning off, the third concept element, the *exit marker*, appears by fading in. This component shows again the next manoeuvre in case there is one following right away. Otherwise, the *exit marker* just points straight as Figure 27d shows.

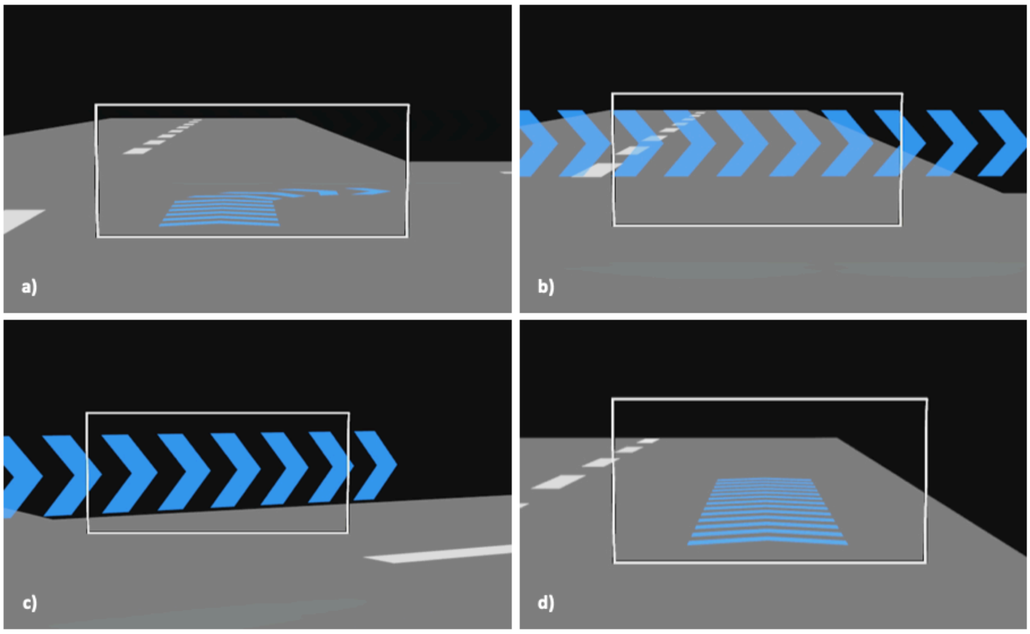


Figure 27: The components of the solid fishbone concept.

7.1.3.2 Dotted Fishbone Concept

The major elements together with their behaviour are the same for both of the navigation concepts examined in this field study. The only difference is that this concept has a dotted fishbone as core element as shown in Figure 28. The idea is that the driver can still recognise and interpret the fishbone shape with the help of the *Gestalt laws of perceptual organisation* (especially the *law of proximity* and the *law of good continuation)*. At the same time, the subject should experience a lower degree of masking the real-world and other road users caused by the virtual content. Although, it might happen that the mental workload of the participant is higher while navigating with the dotted fishbones due to the fact that they might be harder to recognise and interpret than the solid fishbones (Narzt et al., 2006).

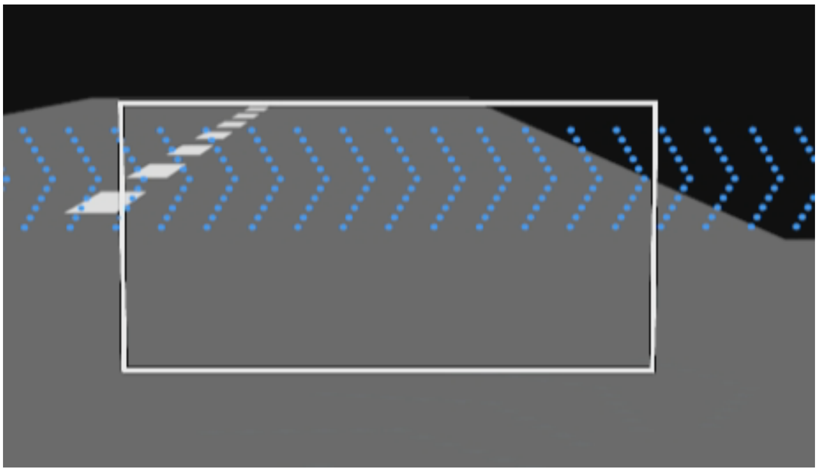


Figure 28: The middle marker of the dotted fishbone concept.

7.1.3.3 Adaption of the Concepts and Test Environment

Both concepts have been adapted multiple times during an agile software development process. Together with experts in the fields of *interaction design* and AR each concept state has been evaluated through sketches, videos, simulations with real vehicle data, and test drives in real traffic.

One of the concept's modifications was the removal of the *exit marker*. Due to imprecise positioning data, the concept element could hardly ever be displayed at the correct position and therefore could not provide an added value.

Next, different parameters which concerned both navigation concepts examined in this experiment had to be defined. Therefore, multiple test drives with the prototype vehicle were taken on the test track used in the study. Table 14 shows a summary of the defined values.

Parameter	**Value**
Entry marker length	7 meters
Entry marker curve (or *r)*	5 meters
Entry marker angle	15,00 degree
Entry marker fade-in distance	90 meters
Middle marker fade-in distance	50 meters
Middle marker length	5,00 x

Table 14: Parameters valid for both navigation concept variants examined in this experiment.

The length of the *entry marker* was set to 7 meters and the value for the curvature of this element was set to 5 meters. Figure 29 explains how the parameters *entry marker length* and *entry marker curve* or *r* are defined, by showing an illustration of an *entry marker* pointing to the right at a turn-off point.

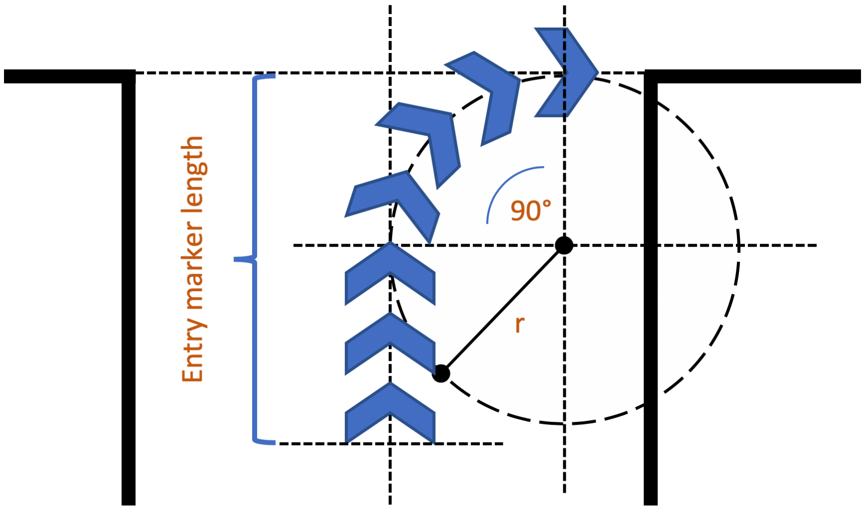


Figure 29: Explanation of parameters entry marker length and entry marker curve (or r).

With the parameter *entry marker angle,* an initial slanted position could be defined by setting its value to 15 degrees. This idea was integrated into a contact analogue navigation concept before by Pfannmueller (2017, pp. 134-135) and thus, better visibility of the concept element in larger distances can be achieved. While approaching the fade-out event of the *entry marker*, the tilt of the *entry marker* is steadily reduced to 0°. Next, the fade-in timing of the markers had to be specified. The fade-in distance of a specific marker can be seen as the distance to the turn-off point in the map. For the *entry marker*, the associated parameter was set to 90 meters. Sometimes, however, it is not possible to display the *entry marker* 90 meters in advance of the turn-off point as the required information cannot always be provided by the road map data in an appropriate time. In that case, the *entry marker* is shown as soon as the data is available. 50 meters in advance of the turn-off point the *middle marker* element fades in while the *entry marker* fades out before. Next, the length of the *middle marker* had to be determined. The value was set to 5 times the width of the determined ego lane (track width of the driver's line).

Another issue that was examined due to the imprecise positioning data was the idea of replacing the contact analogue *middle marker* by a static one anchored in the AR HUD's FOV. This idea was rejected after conducting test drives with experts of both fields, *interaction design* and AR. The main reason was that the experts favoured a pure contact analogue version of the displayed navigation concepts.

7.1.4 Hypotheses

The research goal of this field study was to investigate if a reduction of masking effects can be achieved by applying *Gestalt Principles* (cf. Section 5.1) while maintaining the quality of the information content of the AR HUD navigation cues. One of the main points is to assure that drivers are still able to understand the displayed AR navigation cues by tracking the navigation errors made (H1). Besides that, we evaluated if drivers showed an increase in perceived mental workload when using the *dotted fishbone concept* because of its more difficult recognisability compared to the *solid fishbone concept* (Narzt et al., 2006) (H2). To gain insights into the driver's general and more detailed opinion on the concepts and to be able to further assess the two navigation concept variants and derive ideas on possible improvements, subjective assessment regarding *design, positioning, masking, intuitiveness,* and *distraction* was included (H3). Finally, the driver's user experience connected with the usage of the navigation concepts was evaluated (H4).

Thus, four hypotheses were developed accordingly:

- H1: *The two navigation concepts differ in terms of navigation errors.*
- H2: *The driver's perceived workload is significantly higher for the dotted fishbone concept.*
- H3: *The two navigation concepts differ in terms of subjective assessment.*
- H4: *The two navigation concepts differ in terms of user experience.*

7.1.5 Apparatus and Experimental Setup

In this section the apparatus together with the experimental setup are described. First, further information is given about the prototype car with its built in AR HUD. Next, the components of the software running on the test vehicle are explained and the test track used for the field study is introduced. Further, the demographical data of the participants is summarised and the questionnaires used in the experiment are described. Finally, the procedure of the field study is explained and information concerning statistical methods is given.

7.1.5.1 Experimental Vehicle and Augmented Reality Head-up Display

The experimental vehicle was a long-wheelbase *Mercedes-Benz S-Class V222 series* equipped with an automatic gearbox and a complete AR HUD setup (cf. Figure 30).

Figure 30: The Mercedes-Benz S-Class V222 with exemplary visualisation of the FOV of the integrated AR HUD.

Table 15 shows an overview of the technical data of the integrated AR HUD hardware:

Parameter	Values of Prototype Car
Field of View (W x H)	9.8° x 5.3°
Look Down Angle	Driver (Average Height): 1.8°
Look Over Angle	0°
Image Distance	9.3 m
Vanishing Point Distance	1.5 – 2 m
Eye Box (W x H)	138 mm x 104 mm
Brightness	5000 cd/m^2

Table 15: : An overview of the technical data of the AR HUD used in the conducted field study.

7.1.5.2 Test Environment

As the study took place in a real traffic scenario a suitable prototype vehicle with integrated AR HUD was used as described in the previous section. Further, a predevelopment environment software was created for the test vehicle. It includes the so-called *Robot Operating System* (ROS) (see Koubaa, 2016) which is a set of tools and software libraries that are used to synchronize the vehicle's bus and sensor data such as GPS, gyroscope, accelerometer, and *FlexRay* (see Schätz, Kühnel, & Gonschorek, 2009). To access current map data online, a map interface provided by *HERE maps* was included. With the toolkit *QT* (see Lazar & Penea, 2018) a graphical user interface for AR HUD was created. Furthermore, the *Open Graphics Library* (Open GL) (see Kessenich, Sellers, & Shreiner, 2016) was used as rendering pipeline. The 3D tool *Autodesk Maya* (see Murdoch, 2017) was used together with the image editing software *Photoshop* for the creation of virtual content displayed in the AR HUD.

7.1.5.3 Test Track

As this study was conducted in the field, a suitable test track had to be defined. The route had to be chosen in a way that the results of the test drives could give information regarding the degree of covering traffic objects as well as the suitability of the two navigation concepts for the use case navigation in an AR HUD. For this reason, longer motorway or country road sections with a very little amount of turns were not integrated. Another requirement for getting comparable study results was a consistent traffic density. That's why the experiment was conducted between 9:00 *am* and 4:00 *pm*.

Finally, a test route was chosen that contained almost exclusively streets that are categorized as *level 5* by HERE (2018). That means that most of the time participants had a tempo limit of 30 *kph*. The starting point was around 2.5 *km* away from the *Mercedes Benz Technology Centre* (MTC). That 2.5 *km* were used as a short acclimatisation period for the drivers for getting to know the test vehicle. The test route itself had to be adapted multiple times due to construction works. Another reason for changing parts of the track was that certain turn-off points where not included in the map data and thus, could not be shown in the AR HUD. Another issue was the often-inaccurate height information in the road map data due to sinks or gradients. Eventually, after multiple test drives a route was chosen that is illustrated in Figure 31. The track had a length of 2.5 *km* and contained nine left and nine right turns as well as one manoeuvre where the driver had to go straight. Further, a little roundabout was part of the test track, which had to be passed straight. As this study took place in residential areas with almost exclusively streets with a tempo limit of 30 *kph*, the driver could expect road participants like pedestrians, bicyclists, and cars. This circumstance was useful for the evaluation of the influence of masking caused by virtual content displayed in the AR HUD. The subjects had to complete the test track two times, one time with each AR HUD navigation concept which took them around 20 to 25 minutes in total.

For the prototype vehicle's navigation system, one had to create a file consisting of an array of the test route's waypoints (longitude and latitude). With the help of those waypoints, the car showed the test track's turn-off points even though a free navigation or redirection would have been possible with this system as well.

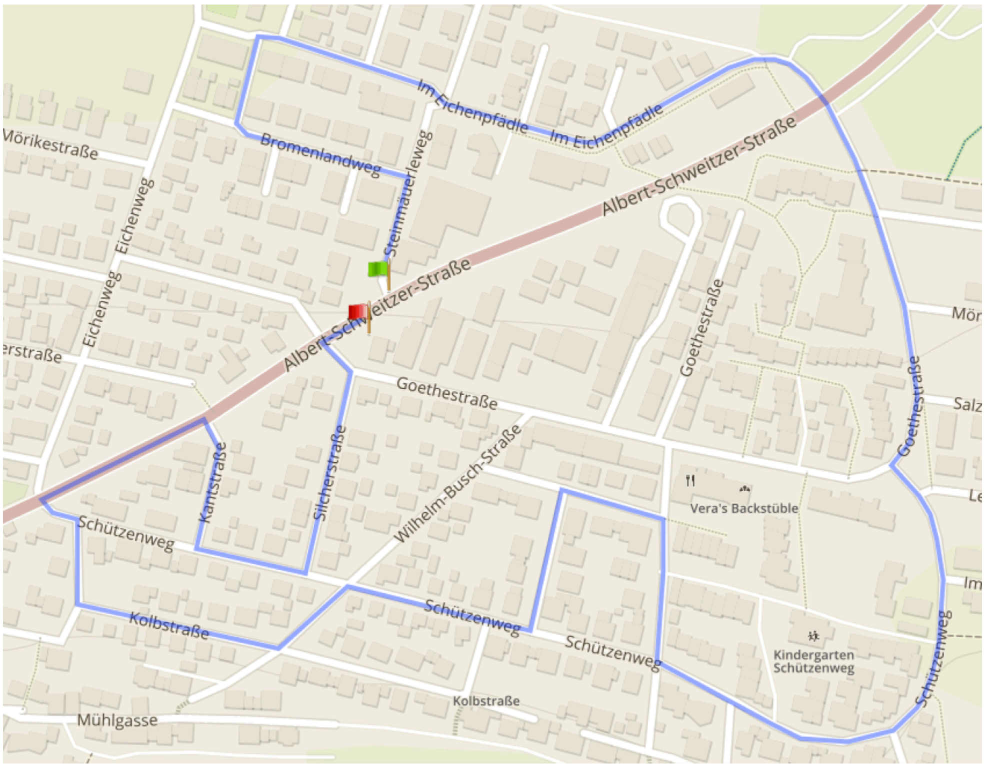


Figure 31: The test track used for the conducted field study.

7.1.5.4 Participants

The participants of this in-the-wild on-road study were employees of *Daimler AG*, all experts in fields relevant for the development of an AR HUD: Interaction design, AR, HUD, design, and sales (area AR HUD).

In total, 26 participants took part in this field study while datasets of 2 test persons had to be removed because of technical problems. From the remaining 24 participants, 5 were female and 19 were male, ranging in height from 1.56 meters to 1.90 meters with $M = 1.79$ meters and $SD = 0.09$. Their age ranged from 22 to 51 years with $M = 34.71$ and $SD = 8.11$ and all participants were holding a valid driving license (category B). The longest length of the driver's license possession was 31 years, whereas the shortest was 4 years, with M = 16.54 and SD = 7.73. Further, 4 subjects had a driving license for motorcycles (category A) and 2 participants were holding a driving license for trucks (category C). The average amount of the approximate number of driven kilometres in the last twelve months was 20250 with a standard deviation of 10279.78. All participants were normal sighted or wore glasses or contact lenses for sight correction.

All drivers had experience with conventional navigation solutions installed on a smartphone or integrated in a vehicle and used them regularly. Figure 32 illustrates how often each navigation device was mentioned by the subjects. Every driver has used a static HUD before but only one participant has one in his private car. The participants' attitude toward HUDs in general was positive. Furthermore, every participant has completed a special driving safety training organised by *Daimler AG* to be allowed to drive the test vehicle used for this field study. All participants were tested individually and gave their written consent to participate in the experiment.

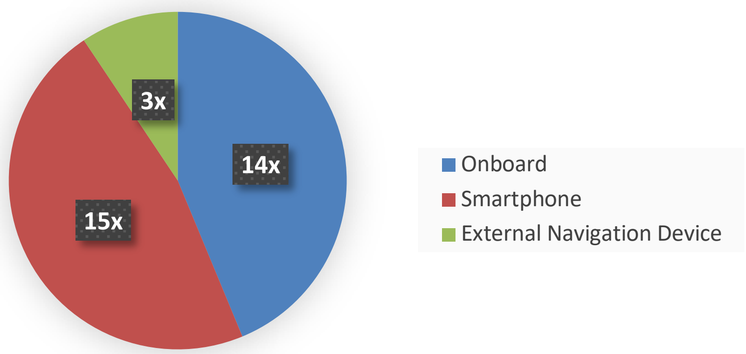


Figure 32: Distribution of subjects' answers regarding what kind of navigation systems they use.

7.1.5.5 Questionnaires

In this section the questionnaires used during the study are described. Subjective mental workload was measured with the *Driving Activity Load Index* (DALI) and user experience was evaluation with the *User Experience Questionnaire* (UEQ). Furthermore, a questionnaire for subjective assessment regarding *design, positioning, masking, intuitiveness,* and *distraction* will be explained and an overview of the open questions asked to the participants is given.

DALI

The *Driving Activity Load Index* (DALI) is a tool designed by Pauzié (2008) that allows the subjective evaluation of the mental workload in the driving context (cf. Appendix A.1). The DALI is a short scale questionnaire based on the NASA-TLX (Hart & Staveland, 1988) and was developed for the automotive context. The tool contains one item for each of the following factors: *Global attentional demand*, *visual demand*, *auditory demand*, *stress*, *temporal demand,* and *distraction*. The driver is asked to give an answer for each of the items on a 6-point Likert scale from 0 (*low*) to 5 (*high*). In the current field study, every participant had to fill this questionnaire after testing each of the two navigation concepts. In the current experiment the factor *auditory demand* was not used as there was no audio output included in the study.

Furthermore, there are other techniques available to measure the mental workload. One example is the *Index of Cognitive Activity* (ICA) which provides an objective measurement of mental workload and is based on changes of the pupil diameter of the subject (Marshall, 2002). However, this technique was not used in this study as there would have been too many disruptive factors in a field study in real traffic, such as alternating brightness.

Another example would be the assessment of mental workload via physiological indicators which can advantageously extend subjective measurements. One of the most used physiological assessment to objectively measure mental workload is the *electrocardiogram* (ECG) which records the electrical activity of the heart. Another physiological measure is called *electroencephalogram* (EEG) which records the electrical activity of the human brain and a final example is the *electrodermal activity* (EDA) which measures changes in electrical skin properties (Brookhuis & de Waard, 2010; Paxion, Galy, & Berthelon, 2014). However, physiological measures usually require additional hardware which has to be connected to the subjects. This could disturb the subjects while driving and thus, physiological measures were not used in this experiment.

UEQ

The *User Experience Questionnaire* (UEQ) measures the user experience of interactive products for six categories: *Attractiveness*, *perspicuity*, *efficiency*, *dependability*, *stimulation*, and *novelty*. It can be found in Appendix A.2. Each participant has to answer the 26 items of the questionnaire which have the form of semantic differentials, i.e. every item consists of two terms with opposite meanings. Further, the terms have a randomised order per item which means that half of the items starts with the positive term and the other half with the negative. To reduce the central tendency bias, a seven-stage scale is used (Hinderks, Schrepp, & Thomaschewski, 2018).

Questionnaire for the subjective evaluation of AR HUD navigation concepts

This self-designed questionnaire was used to assess different concept aspects such as *design, positioning, masking, intuitiveness, distraction,* and *total rating.* The questionnaire can be found in Appendix C.2. The questionnaire was based on a tool used by Pfannmüller (2017, p.. 139-140) for a field study to compare the use case *navigation* in a contact analogue and static HUD. The questionnaire consisted of 19 items that used a 6-point Likert scale, so that the participant had to give at least a little tendency for one of the provided terms. Further, there was one question that used German school grades (1 = *best*, 6 = *worst*).

The first section of the questionnaire contained 10 questions dealing with the design of the current navigation concept: The first four items addressed the design of the current navigation concept regarding its geometrical form in terms of *naturalness*, *width*, *size*, and *dominance*. The following four items dealt with the colour design of the shown virtual content regarding *pleasure*, *sobriety*, *brightness*, and *opacity*. Next, the subjects had to state whether the navigation concept meets their expectations and had to assess it by giving German school grades.

The second section comprised seven questions that addressed the following topics: *positioning of the visual content, masking of the real world, driver distraction,* and *visual perception.* In the last section, the participants had to give an overall assessment by stating whether they were of the opinion that the current navigation concept was well made and after driving with both concepts, the subjects had to decide which navigation aid covers less of the real-world environment.

Open Questions

To find out what drivers liked or disliked about the navigation concepts and what they would like to improve, five open questions were asked. The corresponding questionnaire can be found in Appendix C.3. The first two questions address the facts that the subjects like or dislike about the navigation aids. With the third question, suggestions for improvement can be collected, together with further comments addressing the current concept. The fourth question is dealing with the possibility of combining static and contact analogue content in one navigation concept for AR HUD and how this could be realised. After the participants have seen both of the concepts, the have to compare the variants and state whether they have a favourite and why.

7.1.5.6 Procedure

One of the few in-the-wild on-road studies examining concepts for AR HUDs was conducted by Pfannmüller (2017). A conventional navigation displayed in the car's HUD was compared with navigation for AR HUD. Even though the experiment had limitations like the missing possibility of free navigation with the AR HUD or the usage of a different test vehicle for each HUD type, this study can be used for orientation.

After getting a short introduction to the prototype vehicle, the participants were allowed to adjust the positions of the driver seat, interior and exterior mirrors, as well as air conditioning to their comfort needs. DASs like LDP and BSM were available in the car. The usage of ACC was not allowed as this might have had an influence on the driver's workload.

After taking a short practice route to get accustomed to the test vehicle, the subjects stopped at a parking area next to the test track's starting point and had to sign a consent form. Next, three different test images were shown in the AR HUD while the driver could also calibrate it according to the head position. The first picture contained black and white squares that showed the AR HUD's size to the driver (cf. Figure 33-left). Picture number two consisted of different colour gradients to show the systems display quality (cf. Figure 33-middle). The third picture (cf. Figure 33-right) showed an exemplary contact analogue navigation hint.

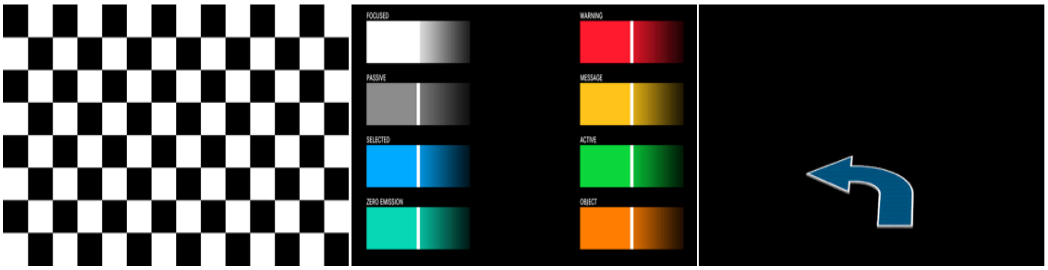


Figure 33: Test pictures shown prior to the conducted field study.

While the examiner started the test software, the subjects filled a questionnaire covering demographical data, driving experience, and experience with HUDs in general. The current weather conditions were logged by the investigator. Next, the participants were given instructions for the study and were told to think aloud during the drives. Every subject had to drive the test route two times with an identical test procedure for both AR HUD navigation concepts. Half of the drivers started with the *solid fishbone concept* and the other half with the *dotted fishbone concept* to compensate learning effects regarding the test track. The experimenter sat on the passenger seat next to the driver while a second person was sitting on the rear bench behind the examiner to log incidents like traffic blocks, system malfunctions, and navigation errors. Additionally, a *GoPro dashcam* was mounted above the head-unit of the prototype vehicle to record a video from each drive together with audio data. Additionally, subjects were asked to tell the examiner in which direction the current navigational cue pointed when not being sure about where to turn off next. This was done to avoid possible rerouting inconsistencies. Figure 34 illustrates the interface of the test vehicle showing an exemplary *middle marker* of the *dotted fishbone concept*.

Figure 34: The interface of the test vehicle showing an exemplary middle marker of the dotted fishbone concept.

After finishing the test track, the subjects filled in the DALI, a tool designed to evaluate the driver's mental workload, and the UEQ to measure the user experience. In addition, a self-designed questionnaire to assess different aspects of each concept like *design*, *positioning accuracy*, *degree of masking*, *driver distraction*, and *perception* was handed out. With the help of open questions, the participants were asked what they liked or disliked about the shown concepts and what they would improve. After the second drive, the subjects had to compare the two concepts and state whether they had a favourite and why.

7.1.5.7 Statistical Methods and Data Analysis

For the DALI, the single item means as well as a global non-weighted mean score for the two concepts were compared. The UEQ items result in six factors that were analysed individually. The self-designed questionnaire was evaluated with a single item analysis as well. *Wilcoxon signed-rank tests* were conducted to compare the means of the ordinal questionnaire data and the non-normally distributed navigation error data. In a second step, we tested order effects with identical methods. The *alpha level* for all analyses was set to .05. Statistical tests were performed in *SPSS* (*Version* 24.0).

7.1.6 Results

This section contains a compilation of the study results, including a descriptive analysis of the navigation errors made by the participants. Next, the outcomes of the inferential analysis of the standardized questionnaires UEQ as well as DALI and the questionnaire for subjective assessment is shown. Finally, the feedback that the experts gave in open questions will be explained and summarised. Isabelle Tessmann supported the data analysis while doing her bachelor thesis together with *Daimler AG*.

7.1.6.1 Navigation Errors

Most (87.87%) of the thirty-three navigation errors that were made in total, happened at three points on the test track. Those points are marked in Figure 35:

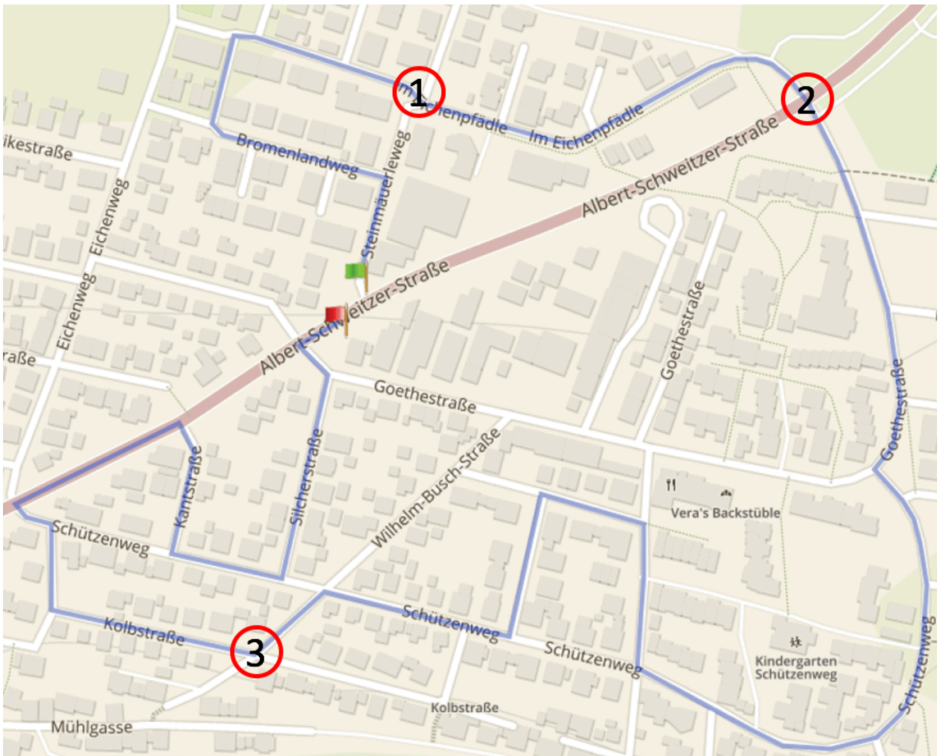


Figure 35: Turn-off points with frequent occurrence of navigation errors for the current field study.

Eight of the navigation errors (24.24%) were made at *point 1*, a little roundabout where participants had to take the second exit which means going straight. More than half (51.51%) of the navigation errors were recorded at turning *point 2* where the drivers had to go straight. Lastly, four navigation errors (12.12%) were made at turn *point 3*. In total, the test track contained 20 manoeuvres with quite similar navigation errors made per subject for the solid fishbones (*M* = 0.71, *SD* = 0.95) and the dotted fishbones (*M* = 0.67, *SD* = 0.70). A *Wilcoxon signed-rank test* indicated that there was no significant difference between the concepts in the navigation errors made per subject (*Z* = - 0.144, *p* = .886). However, further analysis revealed that there was a significant learning effect regarding navigation errors made per subject when comparing the first time (*M* = 1.13, *SD* = 0.92) and the second time (*M* = 0.3, *SD* = 0.47) the participants drove on the test track (*Z* = - 3.28, *p* = .001).

7.1.6.2 User Experience Questionnaire (UEQ)

User experience was measured with the UEQ. A detailed description of the questionnaire is given in Section 7.1.5.5. No significant differences between the two navigation concepts could be found for any category (cf. Table 16).

Category	**M (Solid)**	**M (Dotted)**	**Z**	**p**
Attractiveness	0.96	0.93	- 0.05	.96
Perspicuity	1.57	1.08	- 1.55	.12
Efficiency	1.06	0.97	- 0.18	.86
Dependability	1.1	0.9	- 1.21	.23
Stimulation	1.34	1.09	- 1.35	.18
Novelty	1.0	1.24	- 1.14	.25

Table 16: Results (mean values) of the UEQ per concept.

Table 16 shows the mean UEQ rating for both concepts for each category. Subjects rated the *solid fishbone concept* slightly higher with respect to *perspicuity*, *dependability* and *stimulation* and the *dotted fishbone concept* as more of a *novelt*y. However, further order effect analysis revealed that participants rated whatever navigation concept they saw first significantly higher (*M* = 1.35, *SD* = 0.88) in the category *novelty* compared to the second navigation concept (*M* = .89, *SD* = 0.78), *Z* = - 2.1, *p* = *.04*.

7.1.6.3 Driving Activity Load Index (DALI)

A detailed description of the DALI can be found in Section 7.1.5.5. Figure 36 illustrates the mean subjective rating for the five individual categories as well as the global score. Neither the individual item analysis (*global attentional demand*, $Z = -0.56$, $p = .58$, $r = .08$; *visual demand*, $Z = -0.23$, $p = .82$, $r = .03$; *stress*, $Z = -0.68$, $p = .5$, $r = .1$; *temporal demand*, $Z = -0.83$, $p = .41$, $r = .12$; and *distraction*, $Z = -0.74$, $p = .46$, $r = .11$) nor the *global score* analysis ($Z = -0.05$, $p = .94$, $r = .01$) revealed any significant differences between the two navigation concepts used. Further analysis regarding order effects did not result in any significant finding either.

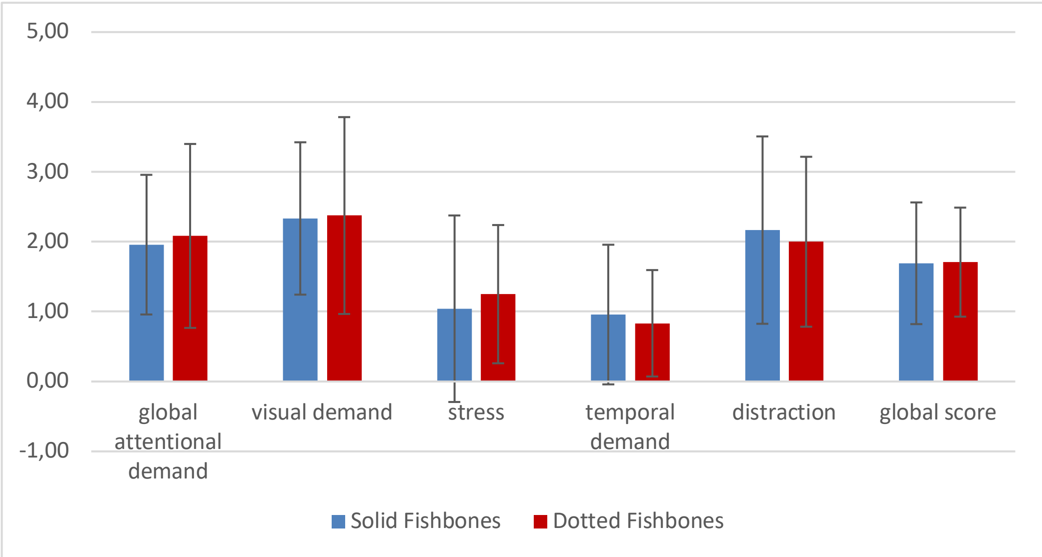


Figure 36: Measured mean values of DALI for solid and dotted fishbones.

7.1.6.4 Questionnaire for Subjective Assessment

The questionnaire for subjective assessment (cf. Section 7.1.5.5) consists of 18 items regarding various categories such as *design, positioning, masking, intuitiveness, distraction,* and *total rating*. Also, the elements *positioning, intuitiveness,* and *visibility* are included. Furthermore, there are two questions on the subjective rating of the concept as a whole. All items are 6-point Likert scales. Table 17 and 18 summarise the significant results only for both concepts.

Subjects rated the displayed content of the *solid fishbone concept* to be significantly narrower and more dominant than the dotted fishbones.

Furthermore, they were perceived as significantly more intrusive, brighter and higher in masking, compared to the *dotted fishbone concept*.

No.	Semantic differentials	M (solid)	M (dotted)	Z	p
1.2	*Too wide (1) - too narrow (6)*	2.96	2.38	-2.58	.01
1.4	*Too dominant (1) – too subtle (6)*	2.33	2.83	-2.08	.04
2.2	*Too subtle (1) - too intrusive (6)*	3.67	3.13	-2.28	.02
2.3	*Too bright (1) – too dark (6)*	3.13	3.46	-2.31	.02
2.4	*Too covering (1) – too transparent (6)*	2.67	3.54	-3.28	< .01

Table 17: Semantic differentials' mean values of significant results.

Although subjects found the solid fishbones to result in significantly more *masking of the real environment* which they found *disturbing* as well, they rated them to be significantly easier to *perceive* and to *recognise and interpret* compared to the dotted fishbones (cf. Table 18).

No.	Statement	M (solid)	M (dotted)	Z	p
7	*I found it easy to recognise and interpreted the displayed navigation hints.*	4.92	4.38	-2.3	.02
8	*The masking of the real world caused by AR content was disturbing.*	3.25	2.17	-2.13	.03
10	*I could perceive the displayed AR HUD content well under the experimental conditions.*	5.58	4.79	-2.68	< .01
11	*In my opinion the concept covered too much of the real environment.*	3.38	2.13	-2.56	.01

Table 18: Mean values of significant results. Rating scales ranging from 1 (strongly disagree) to 6 (strongly agree).

No significant differences between the two concepts could be found in the *perceived mental workload* when using the navigation (Z = - 1.72, p = .09), the *positioning in the real world* (Z = - 1.46, p = .14), the *cut off* (Z = - .12, p = .91) of the AR content and the total *size* of the displayed content (Z = - .89, p = .37), as well as in the *overall rating* ($Z = -.44$, $p = .66$; $Z = -1.78$, $p = .075$). However, there is a trend for the *solid fishbone concept* to be rated slightly lower regarding *perceived mental workload* and higher in the *overall rating* items.

The order effect analysis revealed that item 3 *(the navigation concept fulfilled my expectations)* was rated higher for the first concept used, compared to the second.

7.1.6.5 Open Questions and Think Aloud

Besides standardized and self-designed questionnaires, the participants had to answer open questions after each drive. The applied questions are described in Section 7.1.5.5. Further, the subjects were asked to think aloud during driving and tell the investigator what they liked and disliked about the concepts and what improvement suggestions they would make. The results of both evaluation methods were analysed, evaluated and combined according to the *qualitative content analysis* by Mayring & Fenzl (2014) which is based on the inductive definition of categories. When subjects gave the same information while thinking aloud and answering the open questions, it has only been counted one time. Furthermore, there was feedback that has only been given by one participant. Those individual comments are not mentioned in this section as this would go beyond the scope but can be looked up in the corresponding table included in the Digital Appendix.

The experts gave positive and negative feedback as well as feedback that is valid for both concept variants which is listed in Table 19 and 20. In case of the *solid fishbone concept*, 14 participants mentioned that they appreciate its clearness and intuitiveness. Five experts stated that the bones are easy to recognise also in contrast to the dotted fishbones. Another fact that people liked about the solid fishbones was that in case of being cut off by the limited FOV of the AR HUD one can still draw reliable conclusions on the direction in which the navigation cue is pointing to (mentioned by two subjects). Two participants rated this concept as more contemporary and better designed as the variant with the dotted fishbones. Furthermore, one participant mentioned that he or she had the impression that the solid fishbones keep the driver awake and another subject stated that the navigation hint gives a feeling of safety due to its intuitiveness. The *dotted fishbone concept* was rated as intuitive and clear as well (13 participants) and 11 experts stated that it covers less of the real environment. Five subjects shared the opinion that the dotted fishbones give the impression of being more valuable and delicate and four participants rated the concept as innovative. Additionally, three experts liked the concept's discreet design and two subjects mentioned that they perceived the cutting of the visual content, caused by the limited FOV, as less annoying. Finally, one driver stated that he or she liked the 3D experience perceived with the dotted fishbones in case of accurate positioning. There was positive feedback that was valid for both variants and because of that, it made sense to assign these categories to an own group. Seven subjects mentioned that the navigation cues are pleasant regarding their colour scheme. Also, five participants said that they appreciated the contact analogue positioning of the virtual elements and five subjects mentioned that they liked the fade-in timing of the fishbones. Three participants appreciated the fact that it is no longer necessary to avert the glance in order to see the navigation hints. In addition, three subjects liked that the eyes-off-the-road time was declining as the AR content was placed in their primary FOV.

Solid fishbones concept	Dotted fishbone concept
Intuitive and clear (14)	Intuitive and clear (13)
Easy to recognise (5)	Covers less of the real environment (11)
Manoeuvre can still be recognised in case of cut off (2)	More delicate and valuable than the solid fishbones (5)
Better designed and more contemporary (2)	Innovative (4)
Keep the driver awake (1)	Discreet design (3)
Generate a feeling of safety (1)	Cutting is less disturbing (2)
	3D experience (1)
Colour scheme (7)	
Contact analogue positioning of the concept elements (5)	
Fade-in timing (5)	
No glance aversion necessary anymore (3)	
Decreasing eyes-off-the-road time (3)	

Table 19: Positive feedback for the concept variants in Field Study 1.

Beside positive aspects, also negative points have been mentioned by the participants. Especially size and dominance of the *solid fishbone concept* are described to have a negative effect, especially when the vehicle is close to a manoeuvre point (mentioned by 17 subjects). Furthermore, ten participants criticised the high degree of masking of the real-world environment and other road users caused by the solid fishbones. Four subjects mentioned that when the visual content gets trimmed too much it's not possible to interpret the current turn direction anymore. Four experts stated that they had to concentrate more and also their stress level was increasing while driving with the solid fishbones. Two drivers experienced a strong flickering of the shown AR content while driving with this concept variant and two participants mentioned that the individual markers are too big. In case of the *dotted fishbone concept*, twelve subjects criticised that it is not possible to recognise the turning direction when the AR cues are cut off too much. The reason for that is that the drivers can only see single dots that cannot be put together to a fishbone-shape anymore. Eight participants explained that this navigation concept distracts the driver more and claims a higher amount of cognitive resources. Further, seven subjects mentioned that the navigation cues of the variant with dotted fishbones are difficult to recognise and seven drivers said that the markers are too huge or dominant. An issue that was criticised by four participants was that the driver has to reconstruct the single dots back together to a fishbone first before being able to interpret the shown manoeuvre which costs mental resources. Four experts said that they got disturbed by the fact that the visual content gets cut off sometimes due to the limited FOV of the AR HUD. Further, three drivers mentioned that they experienced a strong flickering of the shown visual elements while driving. There was negative feedback that was valid for both concept variants and for that reason it was assigned to an own section. The sometimes-imprecise positioning of the AR content was mentioned as disturbing by 18 participants and seven experts believed that the transition between *entry marker* and *middle marker* is too abrupt and should be smoother. Six drivers mentioned that the *entry marker* should be shown longer while three participants suggested to increase its size to enhance comprehensibility and visibility. Finally, two experts stated that the *entry marker* should also be displayed earlier.

Solid fishbones concept	Dotted fishbone concept
Size and dominance (17)	Not possible to recognise the manoeuvre anymore in case of strong trimming (12)
High degree of masking (10)	Higher distraction (8)
Not possible to recognise the manoeuvre anymore in case of strong trimming (4)	Navigation cues are hard to recognise (7)
Higher stress level while navigating (4)	Too dominant (7)
Strong flickering of visual content (2)	Mental reconstruction of the fishbone elements required (4)
Elements are too big (2)	Cutting off is disturbing (4)
	Strong flickering of visual content (3)
Imprecise positioning of navigation cues (18)	
Abrupt transition between entry and middle marker (7)	
Entry marker should be displayed longer (6)	
Entry marker too small (3)	
Entry marker should be shown earlier (2)	

Table 20: Negative feedback for the concept variants in Field Study 1.

Besides the positive and negative aspects, the subjects were asked to give suggestions for improvement for both variants which are listed in Table 21. For improving the variant with the solid fishbones, six experts suggested to integrate the possibility to adjust the level of transparency or display the outlines of the shape only. This should help to cover less of the real environment. To soften the design of the *solid fishbone concept*, five participants were thinking about rounding off all edges of the concept elements. To avoid masking of other traffic participants, two subjects had the idea of hiding the visual content generated by the AR HUD in case of oncoming traffic and two participants mentioned that they would like to have further textual indications to improve the comprehensibility of the navigation concept. To achieve better integration in the real world, two experts had the idea of adding animation to the concept. This is also recommended by Milicic (2010) and Pfannmueller (2017) to guide the driver's attention towards important events but at the same time animation should be used carefully and should be easy to understand. Another subject thought about a more precise lower edge of the navigation arrow by using shadows. One of the suggestions for improvement solely mentioned for the *dotted fishbone concept* was the idea of making the single circles more transparent (mentioned by six subjects). Further, two experts suggested to raise the *entry marker* up to create a better flow along the street. In case of a strong cut of the visual content due to the limited FOV of the AR HUD, two experts suggested to use a different graphic rendition and one subject wanted a softer transition between the two markers. Another participant suggested to avoid "driving through" the *middle marker*. Besides, the participants had ideas regarding both variants. These include the possibility of adjusting the displayed content concerning its number of elements, size, brightness, and colour, mentioned by eleven participants for the solid fishbones and by 15 participants for the dotted ones. Furthermore, an improvement of the AR content's positioning was mentioned, seven votes for the *solid fishbone concept* and nine votes for the dotted fishbones. Some participants also had the idea of integrating a pre-indication that contains the direction of the upcoming manoeuvre together with the distance to it (six votes for the solid fishbones and four votes for the dotted ones). A similar suggestion that was stated two times for the solid fishbones and two times for the dotted fishbones is to integrate a permanent notification that indicates that the AR HUD navigation is still running which could be realised with the help of a static route indicator. This is especially useful in case of longer sections without any displayed manoeuvre. Another idea was to extend the display duration of the *entry marker*, stated by three participants in case of the solid fishbones and by two participants in case of the dotted fishbones. The fusion of *entry* and *middle marker* to one element is a suggestion for improvement that was given by three experts in case of solid fishbones and by one expert in case of the dotted ones.

Solid fishbone concept	Dotted fishbone concept
Possibility to adjust level of transparency or display outlines only (6)	Dots should be more transparent (6)
Rounding edges of concept elements (5)	Raise the entry marker up (2)
Hiding AR content in case of oncoming traffic (2)	Display a different graphic in case of strong cut off (2)
Further textual indications (2)	Make transition between markers softer (1)
Adding animation (2)	Avoid “drive-through-effect” (1)
Adding shadows (1)	
Make concept adjustable in terms of size, number of elements, brightness, and colour (11) (15)	
Improve positioning in general (7) (9)	
Integrate a pre-indication (6) (4)	
Add a notification that shows that the system is still running (2) (2)	
Extend display time of entry marker (3) (2)	
Combine entry and middle marker (3) (1)	

Table 21: Suggestions for improvement for the concept variants in Field Study 1.

Next, the participants were asked to give suggestions on how a combination of contact analogue and static content could look like. An overview is given in Table 22. One of the ideas was to display driving assistance information like traffic signs, speed or ACC in a separate status bar (nine votes for the solid fishbones and nine votes for the dotted fishbones). For both concepts, the participants desired to enrich the navigation hints with static content that should be shown in certain situations only (mentioned nine times for the solid fishbones and six times for the dotted ones). Another suggestion was a 2D-pre-indication that displays the upcoming turn-off point together with its distance, stated seven times for the solid fishbones and seven times for the dotted fishbones. Showing static navigation cues in case of the contact analogue content being cut off too much was another idea (one vote for the *solid fishbones* and one vote for the *dotted fishbones*). The inclusion of the estimated arrival time of the current route was mentioned one time in case of the *solid fishbone concept* and one time in case of the *dotted fishbone concept*. Lastly, it was mentioned that it would be helpful for the driver to include a static direction icon to indicate that the AR HUD system is still running (one vote for the solid fishbones and one vote for the dotted fishbones).

Display driving assistance information in a separate status bar (9) (9)
Enrich the navigation hints with static content situationally (9) (6)
Integrate a pre-indication (7) (7)
Show static navigation cues in case the contact analogue ones are cut off too much (1) (1)
Include estimated arrival time (1) (1)
Include a static direction icon (1) (1)

Table 22: Combination of static and contact analogue content. The first number represents the number of mentions in case of solid, the second number in case of dotted fishbones.

When the participants were asked which concept variant they would prefer and for what main reasons, the outcome showed a slight preference towards the *solid fishbone concept*. In total the solid fishbones got twelve votes, the dotted fishbones nine, and three participants had no favourite concept (cf. Figure 37):

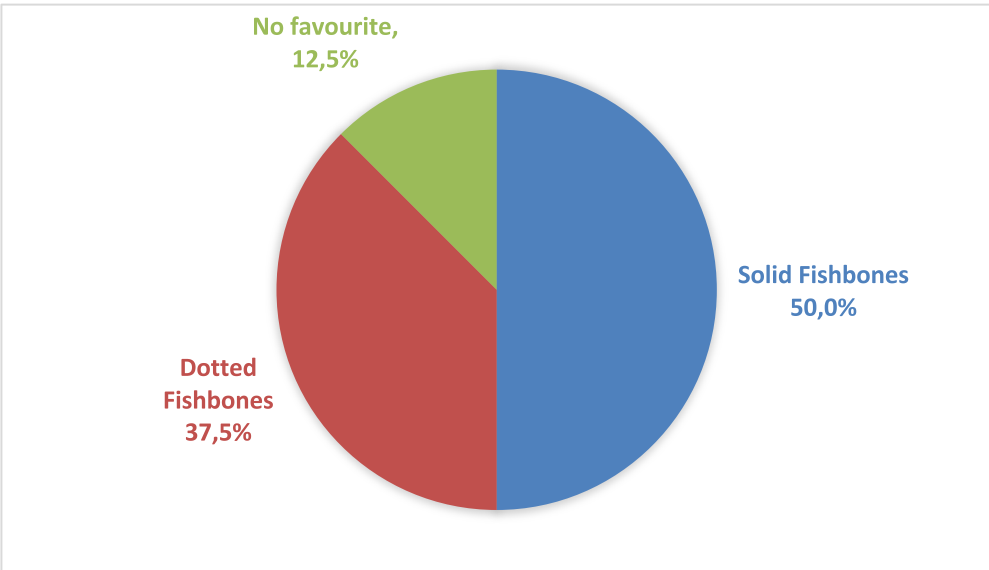


Figure 37: The result of the participant's favourite concept variant.

The drivers gave one or more reasons for choosing a particular concept. In case of the *solid fishbone concept*, six experts stated that this variant is easier to interpret, especially when the visual content is cut off strongly due to the limited FOV. Three participants mentioned that prefer the design of the solid fishbones and one subject explains that the lower cognitive load is one of the key reasons for choosing it. One participant experienced less flickering of the displayed visual content while driving with the *solid fishbone concept* and another subject mentioned that this variant distracts him less. One subject explained that the solid fishbones remind him of objects that are already known and another driver stated that the solid fishbones made her less dizzy during a turning manoeuvre. In case of the *dotted fishbone concept*, six subjects mentioned that they chose it due to experiencing less masking during the drive. Two participants mentioned that their cognitive load was lower while navigating with this concept variant. The design of the concept variant was given as the main reason two times. For one participant the concept's good integration in the real-world environment was a key reason for picking it and another subject mentioned that it was easier to understand and interpret, especially when the visual content is cut off. Finally, one participant said that the enhanced 3D experience is a strong benefit of the *dotted fishbone concept*.

Solid fishbone concept	Dotted fishbone concept
Easier to interpret (6)	Less masking of the real environment (6)
Better design (3)	Lower cognitive load (2)
Less cognitive resources required (1)	Better design (2)
Less flickering of the visual content (1)	Good integration in real world (1)
Less distracting (1)	Easier to interpret (1)
Elements remind the driver of objects that are already known (1)	3D Experience (1)
Less dizziness while turning off (1)	

Table 23: The main reasons for choosing a concept.

7.1.7 Discussion and Conclusion

In the conducted field study, two different navigation concepts for AR HUD were compared in a prototype car equipped with a suitable test environment.

The outcome shows that the amount of navigation errors made with each navigation concept variant was almost the same (cf. *Research Question FS 1.1*). Due to that, H1: *The two navigation concepts differ in terms of navigation errors* was rejected. Most of the navigation errors happened because of inaccurate positioning of the AR content. Further, the participants misunderstood the *middle marker* standing on the edge showing the driver to continue straight and some of the subjects wanted to see a navigation hint at the roundabout. The roundabout in the chosen test track, however, is not integrated as such in the map data. As a result, the navigation system treated the manoeuvre point as *continue straight*, which is why there was no navigational cue.

No significant differences could be found in terms of the driver's subjective workload which was investigated with the DALI questionnaire. Thus, H2: *The driver's perceived workload is significantly higher for the dotted fishbone concept* was rejected as well. However, in the open questions, drivers mentioned multiple times that the concept with the dotted fishbones is distracting and increases the cognitive load. Fewer subjects mentioned this in case of the *solid fishbone concept*. Additionally, there was a trend towards a lower rating for perceived mental workload using the *solid fishbone concept* in the subjective assessment questionnaire. That's why, despite the non-significant results, there is a slight tendency towards a higher cognitive load connected with the dotted fishbones.

The self-created questionnaire containing questions with six-stage scales and German school grades was made to evaluate the shown navigation concepts concerning design, positioning, and distraction. As not all of the given questions showed significant differences, H3: *The two navigation concepts differ in terms of subjective assessment* can only be accepted partly. Overall, the solid fishbones were rated as significantly wider, more dominant, more intrusive, brighter, and has a higher degree of masking. Additionally, the *solid fishbone concept* was rated as significantly easier to recognise and to interpret and also easier to perceive. Furthermore, the majority of the experts thought that the solid fishbones covered more of the real-world environment. They also found that the masking of real objects was more disturbing when driving with the solid fishbone variant. Also, when asked in the open question part which navigation concept they favour with regard to masking, the majority of the experts stated that they would vote for the *dotted fishbone concept,* supporting the results of the subjective assessment questionnaire analysis. Surprisingly, subjects found that whatever concept they saw first, significantly *fulfilled their expectations* more than the second one. Besides that, item (*"The navigation concept fulfilled my expectations.")*, there is one other that assesses the concept as a whole. Looking at the order effects on this second global concept assessment item (*"I think the contact analogue concept as a whole is well-made.")* showed there is a slight non-significant tendency towards a higher rating for the first navigation concept as well. A possible explanation for this could be that subjects were fascinated by the technology as such the first time they saw the AR implementation. Additionally, when seeing the second concept, the drivers were able to draw a comparison and might have had higher expectations. With regard to user experience, the UEQ did not show any significant differences between the two contact analogue navigation concepts, so H4: *The two navigation concepts differ in terms of user experience* can be accepted.

There are several limitations that have to be mentioned. In this field study, the subjects were experts in the respective field of research which was necessary due to the characteristics of the test vehicle used. Although the collected data is valuable from a development perspective, it cannot be transferred to the general population. Our results suggest that participants might be amazed by AR technology when using it for the first time. We counterbalanced the order of the tested concepts to mitigate learning effects, however, the novelty of the technology might still lead to bias in the results. Future research might not be affected by this to that extent because drivers will get more and more used to the technology once an AR HUD is available in production vehicles. Lastly, because the study was conducted in real traffic there were confounding factors that could not be controlled, e.g. the weather or light conditions, slight differences in traffic density, other road users or specific events. Because of those factors, we chose not to analyse vehicle data like breaking and accelerating behaviour. Another reason to not include this in the analysis was that some subjects stopped to take a closer look at the concepts and the displayed content. Also, participants varied a lot in terms of their talkativeness which has been shown to affect driving behaviour (Kramer et al., 2005).

In the foreseeable future, developers will still have to deal with technical limitations like e.g. like package limitations or inaccurate sensor or road map data. For this reason, it is important to create and design robust and flexible UI concepts. In the current study, also an open questions section was integrated to collect expert knowledge concerning navigation concepts for an AR HUD that can be used for future concept development and improvement (cf. *Research Question FS 1.2*). The extensive results comprise positive and negative feedback for the evaluated study concepts, suggestions for improvements, and the combination of static and contact analogue elements in a navigation concept. Finally, the subjects also explained which variant they preferred and for what main reasons.

Some experts had the impression that the visual content in the AR HUD was flickering. Therefore, one of them was asked to look at different screenshots of the navigation concepts in a laboratory setup and to check whether this phenomenon still occurs. In this experiment, an evolved AR HUD hardware was used and the subject could not perceive any flickering. So, it can be speculated that the AR HUD hardware that was used for the field study or the predevelopment software could have been responsible for the flickering effect.

To put it in a nutshell, the usage of *Gestalt Principles* to reduce masking effects provoked by navigation cues or other DASs can be seen as a promising solution. Especially when a lot of virtual information from different use cases needs to be shown in the driver’s primary FOV. Nonetheless, developers need to test whether drivers are still able to recognise and process the big amount of shown information in a sufficient way. Even though the navigation cues were only examined in one specific prototype vehicle, this study can be seen as one of the first approaches to evaluate contact analogue navigation concepts in real traffic. In the upcoming study, a further field study is planned to examine an improved navigation concept for AR HUD. The concept will be created with the help of the findings of this experiment.

7.2 Field Study 2: Further Development of the AR HUD Navigation Concept

For this field study in real traffic, an improved navigation concept for AR HUD was developed, based on the findings of the experiment described in Section 7.1. The findings were analysed by experts in the field of concept development for AR HUD and included in a corresponding navigation concept. To make sure that the newly developed concept is an improvement compared to the *solid fishbone concept*, both concepts were examined in a field study which is described in the following. Like in the previous field study, no audio output was included. The goal was to solely focus on content shown in the AR HUD.

7.2.1 The Harpoon Concept

In this section, elements and behaviour of the improved AR HUD navigation concept, named *harpoon concept*, is described.

As core element the solid fishbones were chosen for several reasons: One of them was that the majority of the participants of *Field Study 1* found that the *solid fishbone concept* is the better concept in general. Reasons for this decision was among others the better interpretability and the better design of the concept. As suggested by some participants of *Field Study 1* this concept consist of one core element which is called harpoon-element and is shaped like a fishbone. The edges are rounded which was a suggestion for improvement of the previous navigation study as well. This element is shown to the driver permanently, placed directly in front of the vehicle and horizontally centred in the FOV (cf. Figure 38). Thereby, one already has the information that the navigation system is still running as wished by some experts that took part in the previous study. Further, the harpoon-element reacts to road irregularities by moving up and down to compensate roll and pitch movements of the vehicle as suggested by (Pfannmueller, 2017, p. 155). This element also covers less of the real-world environment and collisions with real objects like drivers or cyclists are reduced to a minimum.

Figure 38: The core element of the harpoon concept.

When the driver gets closer to the upcoming manoeuvre the harpoon-element will fly to the turn-off point that is marked by a corresponding manoeuvre point available from road map data. This animation is comparable with the movement of a rollercoaster car (cf. DPMA 102020001442.9, n.d.) and should guide the driver's attention towards the upcoming manoeuvre in an unambiguous way as recommended by Milicic (2010, p. 78) and Pfannmueller (2017, p. 164). Next, the harpoon splits into five single fishbone elements. First, only the last fishbone is visible which is directly connected to the manoeuvre point. Figure 39 illustrates the fishbone and its rectangular bounding box. The intersection of both perpendicular bisectors of this bounding box is the point that is connected to the manoeuvre point.

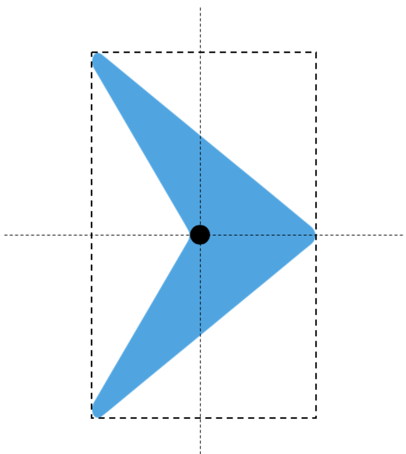


Figure 39: Connection of last fishbone and manoeuvre point.

Next, the remaining four fishbones fan out, appearing out of the last one pointing into the direction of the manoeuvre (cf. Figure 40). Figure 41 illustrates the fishbones implemented in the prototype vehicle which was used for the experiment. These two subtle animations are used to guide the driver's attention towards the next turn-off point in the right moment, as recommended by Milicic (2010) and Pfannmueller (2017). Also, the abrupt transition between two markers, which was criticised in the previous field study, can be avoided by that and a combination of the single concept elements is achieved.

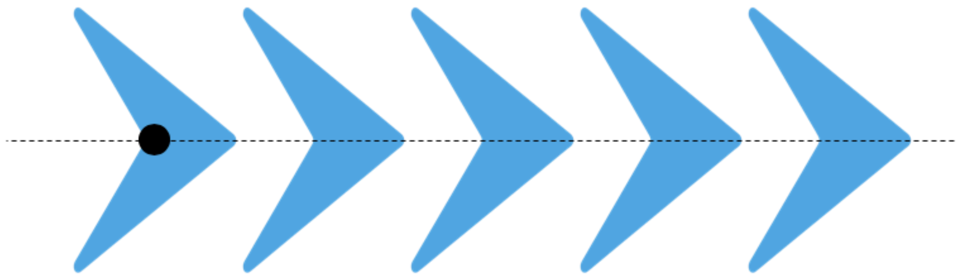


Figure 40: All fishbones together with connection to the manoeuvre point.

Figure 41: The fishbones showing the turn-off direction.

The fishbones are connected with the street in a contact analogue way, standing on the lower edge. At the same time, the fishbones tilt backwards corresponding to the angle between vehicle and fishbones (which are pointing in the direction of the current manoeuvre). Figure 42 illustrates this relation. This tipping behaviour was integrated to clarify the curve shape.

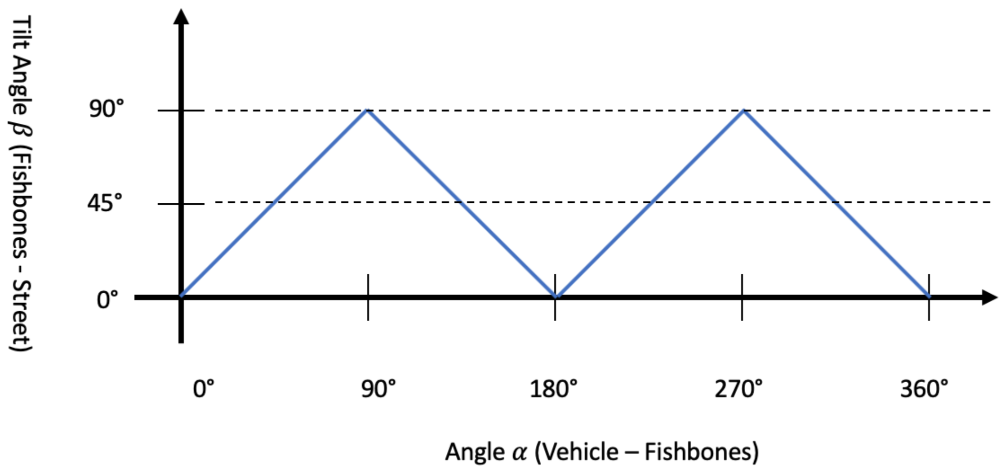


Figure 42: The tipping behaviour of the fishbones corresponding to the angle between vehicle and fishbones.

In case of a manoeuvre that points straight, the fishbones are shown flat on the street with an initial slanted position (angle between street and fishbones = 15°) that is continuously reduced to zero while the vehicle comes closer to the turn-off point. This tipping behaviour was integrated to make it easier for the driver to recognise navigation cues that point straight.

Furthermore, the decision was made to have only one contact analogue state in this concept, which is when the bones fly to the manoeuvre point and fan out, due to the technical limitations concerning the positioning accuracy of visual content in the AR HUD which will also persist in the near future. While getting closer to the manoeuvre point, the fishbones' level of transparency increases in a steady way until only the outlines of the elements remain visible as Figure 43 illustrates. Thereby, the degree of masking caused by the fishbones is reduced. This was suggested by some participants of the previous study as well as by Livingston et al. (2003).

Figure 43: The fishbones showing the turn-off direction while only the outlines remain visible.

To deal with the problem of fishbone-elements becoming too large and dominant while the driver approaches the turn-off point, a so-called pick-up point was included in this navigation concept. Before parts of the fishbones would leave the FOV, they do not get bigger anymore and stay the same size. They stay at a fixed position and are pushed ahead of the car until the current manoeuvre is completed. Unfortunately, this behaviour leads to a loss of the contact analogue behaviour but the participants can still interpret the shown manoeuvre and do not get disturbed by large fishbones in their primary FOV. Another feature of this concept is linked to the fact that the fishbones cannot leave the FOV anymore. Thereby, the driver can see the complete navigation cue at any time and does not get disturbed by fishbone elements that get cut-off. If the bones should e.g. exit on the right side, they would just be stopped and kept inside of the bounding box which is the AR HUD's FOV (cf. Figure 44).

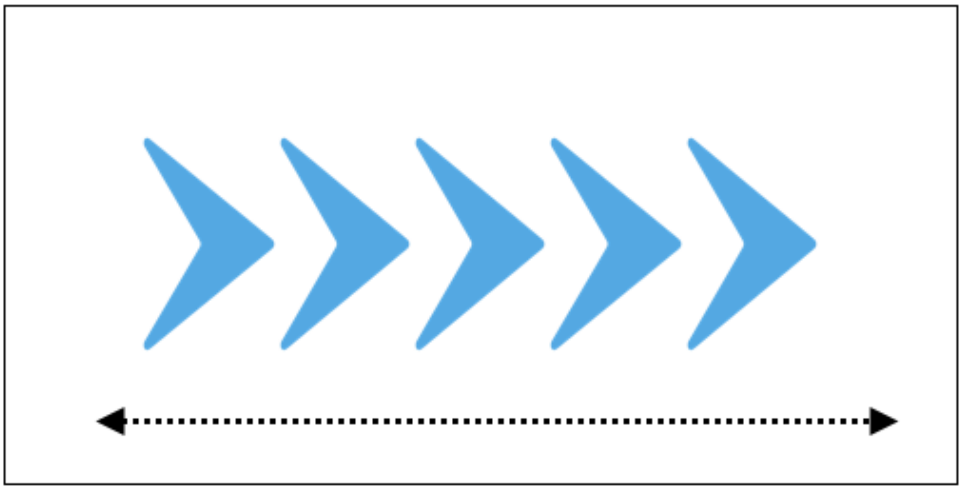


Figure 44: The bounding box, which equals the FOV.

After the current turn was made, which means the current manoeuvre point has been passed by the vehicle, the single fishbones are moving back together while all elements move back in the last fishbone element. At the same time, the fishbones fly back to their initial position and finally, only the initial harpoon-element is shown in front of the vehicle. This animation is again comparable with the movement of a rollercoaster car. Furthermore, as suggested by participants of *Field Study 1*, a pre-indication with distance to the next turn-off point was added to the concept. In case of a turn-off point to the left, the preview is placed at the bottom left and vice versa. In case of a manoeuvre pointing straight, the indication is shown on the right bottom side. This can be seen as a further navigation hint as well as a notice that the navigation is still active. In addition to the pre-indication, further static displays were included: The current vehicle speed as well as a symbol representing the status of the *Distronic* function. As recommended by (Pfannmueller, 2017, pp. 163-164) the status bar was kept simple and minimalistic to not overload the overall AR HUD navigation.

7.2.2 Adaptions of the Harpoon Concept

Before this field study could be conducted, the examined concepts had to be adapted multiple times within an agile software development process. Together with experts in the fields of *interaction design* and AR each state of both navigation concepts has been evaluated with the help of sketches, videos, simulations with real vehicle data, and test drives in a real traffic scenario. As result, different concept parameters could be determined which are listed in Table 24.

Parameter	**Value**
Trigger Distance	100 m
Harpoon Duration	2000 ms
Fan-out Duration	1000 ms
Spacing	1,00 m
Fading Factor	25 %
Harpoon Count	5

Table 24: An overview of the parameters of the harpoon concept.

The parameter named *trigger distance* describes the distance to an upcoming manoeuvre in which the harpoon starts to fan out when the corresponding data is available. Otherwise, the system will wait until the required road map data is sent to the vehicle. The value for this parameter was set to 100 meters. The *harpoon duration* represents the time that it takes until the single harpoon element has moved to the current manoeuvre point without the fan out animation. The value for the duration of this animation was determined to be 2000 milliseconds as the experts had the impression of a smooth animation that is not disturbing by choosing this number. The parameter *fan-out duration* describes the time the fishbones need to fan out after the harpoon moved to the corresponding manoeuvre point. The appropriate value was set to 1000 milliseconds and thus, this animation is faster than the previous one. Thereby, the driver perceives a difference and recognises clearly when the fishbones fan out in a specific direction. The value *spacing* describes the distance between two fishbones other which is the space between the intersections of both perpendicular bisectors of the objects' bounding boxes (cf. Figure 45).

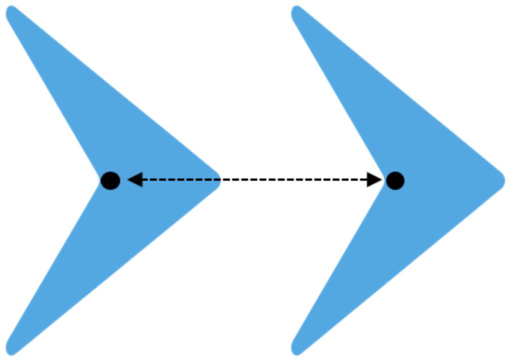


Figure 45: Explanation of the parameter spacing.

The *fading factor* describes the moment when the fishbones start to get transparent. This value is given in percentage and is related to the parameter trigger distance. For this study, the fading factor is 25 % which means that the fishbones start to get transparent 25 meters before approaching the current manoeuvre. The reason for choosing this specific number was that the virtual objects should at first be completely opaque so that drivers can recognise and interpret them better in larger distances. While getting closer to the turn-off point, the points should get more transparent to avoid masking of real objects. The parameter *harpoon count* was set to 5. The reason for this was the circumstance that the fishbones are hard to perceive and a greater amount of single fishbone elements makes it easier for the driver to recognise them together with the direction they point into.

7.2.3 Hypotheses

For the upcoming field study, corresponding hypotheses had to be defined. As the *harpoon concept* is a revised version of the *solid fishbone concept*, one had to investigate whether this navigation concept for AR HUD is rated and works better than the original fishbones. It was important to assess whether it was easier for the participants to navigate with the new concept. This should be tested in terms of navigation errors (H1), trust in the system (H2) and subjective mental workload (H3). Further, the subjects had to give an extensive subjective concept assessment with regard to *design*, *positioning*, *perception*, *animation*, and *total rating* (H4).

The defined hypotheses are listed below:

- H1: *Drivers make less navigation errors while using the harpoon concept.*
- H2: *Drivers have a higher trust in the navigation with the harpoon concept.*
- H3: *The drivers' subjective workload is lower for the harpoon concept.*
- H4: *Drivers rate the harpoon concept better in terms of subjective assessment.*

7.2.4 Apparatus and Experimental Setup

In this section the apparatus and experimental setup are described. The test vehicle, test environment, and test track are the same as in *Field Study 1* and are explained under 7.1.5.

7.2.4.1 Participants

In total, 24 participants took part in this field study while the datasets of 4 subjects had to be removed due to technical problems. All of the remaining 20 participants of this in-the-wild on-road study were employees of *Daimler AG.*

From the remaining 20 participants, 5 were female and 15 were male, ranging in height from 1.64 meters to 1.90 meters with M = 1.77 meters and SD = 0.08. Their age ranged from 25 to 53 years with M = 32.70 and SD = 6.74 and all participants were holding a valid driving license (category B). The longest length of the driver's license possession was 36 years, whereas the shortest was 1 year with M = 14.60 and SD = 8.51. Further, 10 subjects had a driving license for motorcycles (category A) and 2 participants were holding a driving license for trucks (category C). The average amount of the approximate number of driven kilometres in the last twelve months was 15750 with a standard deviation of 7873.17. All participants were normal sighted or wore glasses or contact lenses for sight correction.

All subjects had experience with conventional navigation solutions installed on a smartphone or integrated in a vehicle and the majority of the drivers used them regularly. Figure 46 shows how often the participants mentioned each of the two navigation devices. Every participant but one has used a static HUD before and one driver has a HUD in his private car. The majority of the participants had a positive attitude towards HUDs (cf. Figure 47) and some said that this technology has the potential to replace traditional displays like the *instrument cluster*. However, a few subjects found that this technology is still too expensive. Furthermore, every participant has completed a special driving safety training organised by *Daimler AG* to be allowed to drive the test vehicle used for this field study. All participants were tested individually and gave their written consent to participate in the experiment.

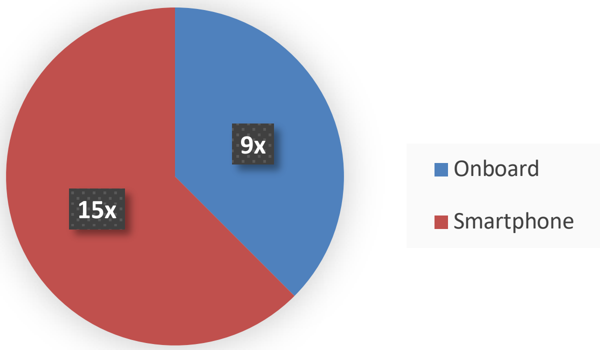


Figure 46: Distribution of subjects' answers regarding what kind of navigation systems they use.

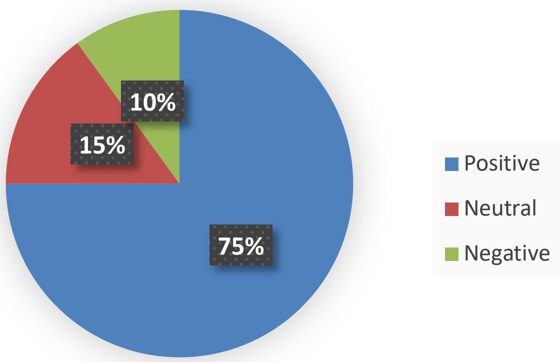


Figure 47: The participants' attitude towards HUDs in general.

7.2.4.2 Questionnaires

In this section the questionnaires used during the study are explained. Subjective mental workload was measured with the DALI that has been described in Section 7.1.5.5. The trust in the system used was evaluated with a tool called *Trust Scale*. Furthermore, a questionnaire for subjective assessment regarding *design*, *positioning*, *perception*, and *animation* will be explained and an overview of the open questions asked to the participants is given.

Trust Scale

The *Trust Scale* was developed to assess trust between humans and automated systems and has the potential to help developers and designers how certain system characteristics could affect the users' perception of trust (Jian, Bisantz, & Drury, 2000). The scale can be found in Appendix A.3. In this study the tool was used to measure the feeling of trust towards the corresponding navigational aids. The questionnaire consists of 12 items. The first five items are dealing with distrust in an automated system and the remaining seven are dealing with trust accordingly. Every item consists of a 7-point Likert scale with the endpoints *not at all* and *strongly*. When assessing the data, the first five questions addressing distrust have to be reverse scored and subsequently, the mean value has to be calculated over all 12 items.

In addition to system trust, it would also make sense to assess the driver's technology acceptance with methods such as the *Technology Acceptance Model* (TAM) (Davis, 1986; Davis, Bagozzi, & Warshaw, 1989). This model helps researches to evaluate why people are using technologies and focuses on three main factors: The perceived usefulness, the perceived ease of use, and the attitude toward use (Taherdoost, 2018). However, we covered these factors with the questionnaire of subjective evaluation of AR HUD navigation concepts, the think-aloud method, and the open questions asked to the subjects.

Questionnaire for the subjective evaluation of AR HUD navigation concepts

This self-designed questionnaire used in this field study is used to assess different concept aspects such as *design*, *positioning accuracy*, *degree of masking*, *driver distraction*, *perception*, and *animation*. The tool can be found in Appendix D.2. The questionnaire is similar to the corresponding one used in *Field Study 1* with a few adaptions.

First, the order of the endpoints of the 6-point Likert scales was alternating to keep the participant's attention. Next, the question in the second section of the questionnaire, addressing the cutting of the virtual fishbones at the edge of the AR HUD's FOV, was removed. The reason for this was that the results of *Field Study 1* showed clearly that the majority of drivers did not like the cutting of visual content. Instead, four items addressing the topic *animation* were added to section two of the questionnaire. The subjects should assess the integrated animation of the current concept in terms of degree of support while navigation and degree of sobriety. Further, they should tell whether they find the shown animation pleasant and well designed. With those four items, a first impression on the effect of varying degrees of animation could be investigated.

<u>Open Questions</u>

To find out what the participants liked or disliked about the current navigation concept and what they would improve, open questions were asked after each drive. The questionnaire can be found in Appendix D.3. After the subjects had seen both concepts, they had to ask two additional questions: The first one was integrated to evaluate whether the *harpoon concept's* stronger animation supported them while navigating or not and why. In the last question, they had to compare the two concepts and state whether they have a favourite one and why.

7.2.4.3 Procedure

The procedure of this study was similar to *Field Study 1* with a few changes.

After getting a short introduction to the prototype vehicle, the participants were allowed to adjust the positions of the driver seat, interior and exterior mirrors, as well as air conditioning to their comfort needs. DASs like LDP and BSM were available in the car. Also, in this study, the usage of ACC was not allowed as this might have influenced the driver's workload.

Next, the participants calibrated the HUD according to their head position and took a short practice route to get accustomed to the test vehicle. Furthermore, the current trajectory of the steering angle was shown in the AR HUD to get a first impression of the system (cf. Figure 48). We added this functionality as the participants of this study were no experts in fields related to AR HUD development. After stopping at a parking area close to the test track, a consent form was filled, and three test pictures were shown in the AR HUD (cf. Section 7.1.5.6).

Figure 48: Visualisation of the steering angle in the AR HUD.

While the examiner started the test software, the subjects filled a questionnaire covering demographical data, driving experience, and experience with HUDs in general. The current weather conditions were logged by the investigator. Next, the participants were given instructions for the study and were told to think aloud during the drives. Every subject had to drive the test route two times with an identical test procedure for both AR HUD navigation concepts. Half of the drivers started with the *solid fishbone concept* and the other half with the new development *harpoon concept* to compensate learning effects concerning the test track. The experimenter sat on the passenger seat next to the driver while a second person was sitting on the rear bench behind the examiner to log incidents like traffic blocks, system malfunctions, and navigation errors. Additionally, a *GoPro dashcam* was mounted above the head-unit of the prototype vehicle to record a video from each drive together with audio data. If subjects were insecure about interpreting the navigational cues, they were asked to tell the examiner in which direction the navigational cue pointed. This was done to avoid possible rerouting inconsistencies. Figure 38 and 41 illustrate the interface of the prototype car showing the harpoon element and the fishbones of the *harpoon concept*.

After finishing the test track, the subjects filled in the *DALI* a tool designed to evaluate the driver's mental workload. Also, they had to fill the *Trust Scale* that was developed to measure trust between people and automated systems. In addition, the subjects had to fill a self-designed questionnaire to assess different concept aspects like *design*, *positioning accuracy*, *degree of masking*, *driver distraction*, *perception*, and *animation*. Finally, participants had to answer open questions in which they should answer what they liked and disliked about the shown concept and what suggestions for improvements they would have. After the second drive, subjects had to state whether the more pronounced animation of the *harpoon concept* supported or disturbed them while navigating. Also, they had to decide which concept they liked more and explain why.

7.2.4.4 Statistical Methods

The results of the single *Trust Scale* items were commutated and a mean *trust score* was calculated for every subject. The means of the *trust scores* for each concept were compared using a *Wilcoxon signed-rank test*. For the DALI, the single item means as well as the global non-weighted mean scores for the two concepts were compared. The self-designed questionnaire was evaluated with a single item analysis as well. Again, *Wilcoxon signed-rank tests* were conducted to compare the means of the ordinal DALI and subjective assessment questionnaire data as well as the non-normally distributed navigation error data. In a second step, we tested order effects with identical methods. The *alpha level* for all analyses was set to .05. Statistical tests were performed in *SPSS* (Version 24.0).

7.2.5 Results

This section provides a compilation of the outcomes of the experiment including a descriptive analysis of the navigation errors made by the subjects. Further, the results of the inferential analysis of the standardized questionnaires *Trust Scale*, DALI, and the questionnaire for subjective assessment are given. Finally, the feedback that the experts gave on the shown navigation concepts by answering open questions will be shown. Anna Bruder supported the data analysis while doing an internship at *Daimler AG*.

7.2.5.1 Navigation Errors

All subjects made a total of 20 navigation errors. Most of them were recorded at four manoeuvre points (cf. Figure 49). The highest error rate of 30% (6 navigation errors) was observed at *point 1*, a straight manoeuvre, followed by 20% (4) at point 2, the little roundabout on the test track. *Point 3* and *4* caused 15% and 10% of the navigation errors, respectively.

The test track contained 20 different manoeuvres. The average navigation error per subject varied between the trip with the *solid fishbone concept* (M = 0.65, SD = 0.88) and the *harpoon concept* (M = 0.35, SD = 0.49), however, the difference turned out to be non-significant (Z = - 1.29, p = .098). Further analysis regarding order effects revealed a significant difference between the first (M = 0.8, SD = 0.83) and the second time (M = 0.2, SD = 0.41) participants drove around the test track (Z = - 2.59, p = .01).

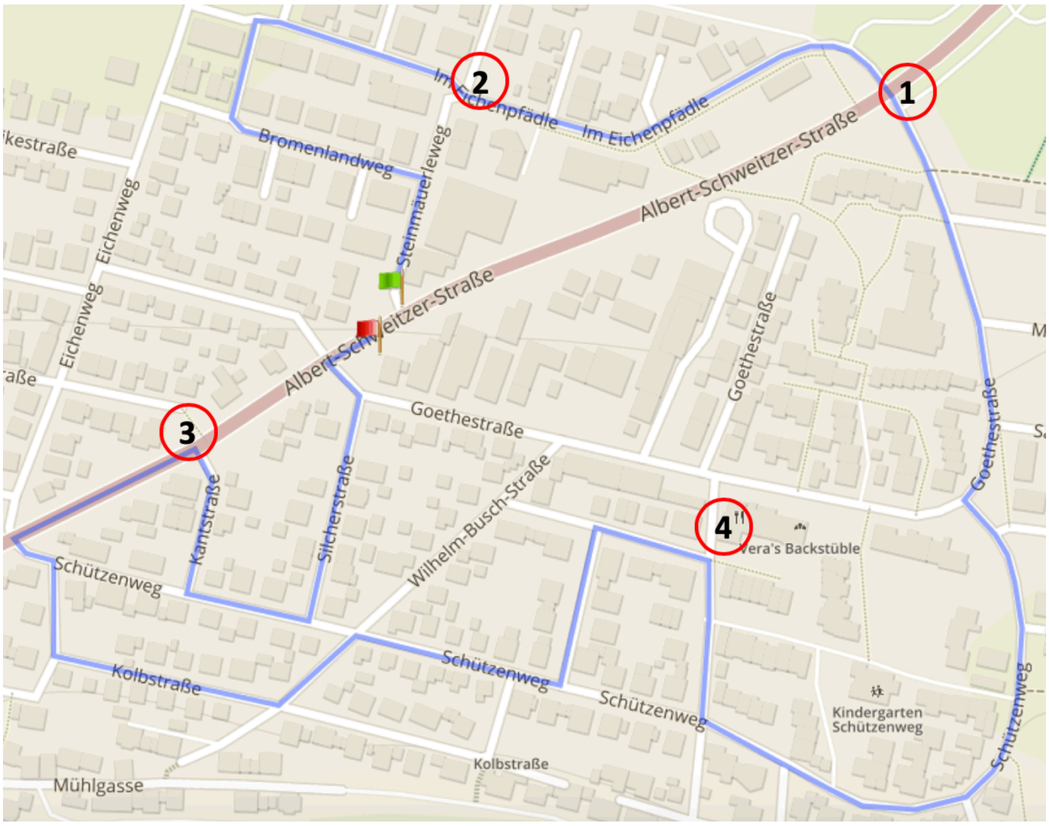


Figure 49: : Turn-off points with frequent occurrence of navigation errors for Field Study 2.

7.2.5.2 Trust Scale

A detailed description of the *Trust Scale* can be found in Section 7.2.4.2. The *trust score* for the fishbone navigation concept is significantly lower (M = 4.71, SD = 1.11) than for the harpoon navigation concept (M = 5.57, SD = 0.76), Z = - 3.29, p = .001. There was no significant order effect on the *trust score*.

7.2.5.3 Driving Activity Load Index (DALI)

A detailed description of the DALI can be found in Section 7.1.5.5. Figure 50 shows the mean values of the participants' subjective ratings for both, the single categories and the global score of DALI for each concept. There were significant differences between the two concepts for the *global attentional demand* (Z = - 1.72, p = .04), the *visual demand* (Z = - 2.51, p = .006), *stress* (Z = - 3.09, p = .001), *temporal demand* (Z = - 2.37, p = .009), and the *global DALI score* (Z = - 2.61, p = .0045). Solely for the *perceived distraction* no significant difference between the fishbone and the *harpoon concept* were found (Z = - 0.39, p = .35).

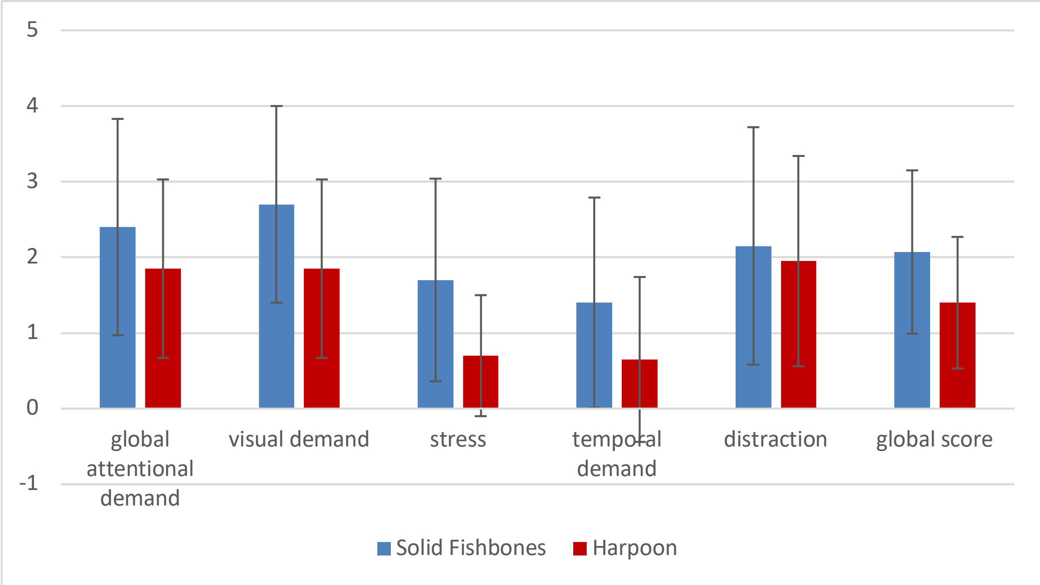


Figure 50: Mean scores of DALI for the Fishbone and the Harpoon Navigation Concept.

7.2.5.4 Questionnaire for Subjective Assessment

A detailed description of the utilized questionnaire for the subjective assessment of the navigation concepts is given in Section 7.2.4.2. The following Tables 25-28 summarise the results and are sectioned topically or based on the underlying scale. All items regarding the subjective assessment of the graphical depiction (cf. Table 25) and the colour design (cf. Table 26) of the navigation concepts revealed significant differences between the fishbone and the *harpoon concept*. The *harpoon concept* was rated more natural and more balanced in width, total size and dominance than the *solid fishbone concept* (cf. Table 25). Regarding colour design, subjects thought the *harpoon concept* was more pleasant, less intrusive, darker, and less covering than the *solid fishbone concept*.

Item	M (FB)	M (HP)	Z	p
1.1: very unnatural (1) – very natural (6)	2.95	4.8	-3.66	< .001*
1.2: too wide (1) – too narrow (6)	1.75	3.38	-3.79	< .001*
1.3: too small (1) – too big (6)	5.25	3.63	-3.56	< .001*
1.4: too dominant (1) – too subtle (6)	2	3.13	-3.27	< .01*

Table 25: Mean values of semantic differentials addressing the depiction of the two navigation concepts fishbone (FB) and harpoon (HP).

Item	M (FB)	M (HP)	Z	p
2.1: very unpleasant (1) – very pleasant (6)	3.9	4.75	-2.5	< .05*
2.2: too subtle (1) – too intrusive (6)	4.2	3.53	-2.1	< .05*
2.3: too bright (1) – too dark (6)	2.9	3.43	-2.19	< .05*
2.4: too covering (1) – too transparent (6)	2.4	3.23	-3.28	< .01*

Table 26: Mean values of semantic differentials addressing the colour design of the navigation concepts fishbone (FB) and harpoon (HP).

Table 27 summarises the results of the items with an underlying 6-point Likert scale. For almost every item, there was a significant difference between the ratings for the harpoon and the *solid fishbone concept*. The *harpoon concept* fulfilled the participants' expectations more, was given a better grade, and was positioned more accurately in the real world compared to the *solid fishbone concept*. Furthermore, subjects thought the navigational content of the *harpoon concept* was easier to recognise and to interpret and caused less masking of the real environment than the navigation hints of the *solid fishbone concept*. Lastly, the participants rated the *solid fishbone concept* to require more of their concentration and rated the *harpoon concept* higher in terms of how well it is made as a whole. Solely for how easy it was to perceive the AR HUD content under the given test conditions, such as light and weather the mean values were the same for both concepts (see item 9 in Table 27).

Item	M (FB)	M (HP)	Z	p
3: the navigational concept fulfilled my expectations.	3.55	5.25	-3.62	< .001*
4: Please rate the navigation concept using German school grades (1 – 6).	3.6	2	-3.6	< .001*
5: I thought the positioning accuracy of the navigation concept in the real world was good.	2.75	4.25	-3.16	< .01*
6: I found it easy to recognise and interpret the displayed navigation hints.	4.3	5.35	-3.31	< .01*
7: The masking of the real world caused by AR content was disturbing.	3.7	2.35	-2.54	< .05*
8: Using the navigation concept required my full concentration.	3.4	2.7	-1.7	< .05*
9: I found it easy to perceive the AR HUD content under the given test conditions (light, weather).	5.2	5.2	-0.16	.437
10: In my opinion the concept covered too much of the real environment.	3.3	1.6	-3.2	< .01*
12: I think the contact analogue navigation concept as a whole is well made.	3.55	5.1	-3.3	< .01*

Table 27: Mean values of questions with a 6-point Likert scale. Rating scale ranging from 1 (does not apply) to 6 (does apply).

The results of the four items regarding the integrated animation are stated in Table 28. Subjects rated the animation of the *harpoon concept* to be significantly more supporting, more pleasant and better designed compared to the *solid fishbone concept*. There was no significant difference in the dominance of the animation between the ratings for the two concepts.

Item	M (FB)	M (HP)	Z	p
11.1: disturbing (1) – supporting (6)	3.5	4.9	-2.85	< .01*
11.2: too distinct (1) – too subtle (6)	2.75	3.2	-1.18	.119
11.3: unpleasant (1) – pleasant (6)	2.95	4.5	-2.89	< .01*
11.4: poorly designed (1) – well designed (6)	2.6	4.65	-3.86	< .001*

Table 28: Mean values of semantic differentials addressing the integrated animation.

7.2.5.5 Open Questions and Think Aloud

Besides standardised (DALI and *Trust Scale*) and self-designed questionnaires, the subjects answered open questions after driving with each concept variant. Those questions are described in Section 7.2.4.2. Further, the participants were asked to think aloud while navigating and tell the investigator what they liked or not concerning the variants and what suggestions of improvement they would integrate. The results of both methods were analysed, evaluated and combined according to the *qualitative content analysis* by Mayring & Fenzl (2014). This evaluation method is based on the inductive creation of different categories. When participants gave the same information when answering open questions and thinking aloud, the corresponding statement has only been counted once. Also, there was concept feedback that has only been given by one subject. Those individual statements are not mentioned in this paragraph as this would go beyond the scope but are listed in the corresponding section included in the Digital Appendix.

First of all, the participants were asked what they like about each concept, whereas some feedback was mentioned for both concept variants. An overview of the given feedback is given in Table 29.

In case of the *solid fishbone concept*, five participants stated that they appreciated the way that the *entry marker* illustrates and clarifies the direction in which the driver hast to turn. Four subjects liked the good visibility and prominence of the displayed visual elements, whereas the good timing of the concept elements was mentioned three times. Also, three participants explained that the contact analogue behaviour of the concept could be seen as a promising step towards enhancing driving safety. The combination of *entry* and *middle marker* was rated positively by three drivers and the fact that there was no permanent display of visual content was appreciated by two.

In case of the *harpoon concept,* there was positive feedback as well. Ten subjects liked the design of the included animation and eight drivers appreciated the positioning of the display together with the good visibility. Seven drivers stated that they like the permanent display of the harpoon element and five subjects found that the concept is not covering too much of the real environment. Four participants mentioned that a contact analogue navigation has an advantage over the conventional variant. Furthermore, four drivers liked the timing of the integrated animation and four participants stated that navigating with this concept is pleasant as well as enjoyable. Also, four drivers appreciated the fact that the surface of the fishbones become more transparent until only the outlines remain visible while approaching them. Three subjects mentioned that they liked the colour scheme and the design of the concept elements and three participants said that they found the static display of the remaining distance helpful. Further, three drivers stated that the representation of manoeuvres pointing straight was well made, two subjects said that driving with this navigation concept is fun, and two participants stated that the *harpoon concept* prepares the driver to an upcoming turn-off point in a right way. The subtle display of the visual elements was appreciated two times and the positioning of navigation information in the driver's primary FOV was mentioned two times as well. Finally, two subjects were of the opinion that the concept enhances the systemic trust and two participants liked the roll-pitch compensation integrated into the concept.

There was also positive feedback that drivers gave in case of both concepts. The statement that the current concept was intuitive and easy to understand was given two times in case of the *solid fishbone concept* and two times in case of the *harpoon concept*. Furthermore, two drivers thought that the solid fishbones are not distracting while driving, whereas eight participants thought so for the *harpoon concept*.

Solid Fishbones Concept	Harpoon Concept
Display of turning direction via entry marker is well made (5)	Design of animation (10)
Visibility of visual elements (4)	Positioning of visual content (8)
Timing (3)	Permanent display of harpoon element (7)
Contact analogue behaviour increases security (3)	Not covering too much (5)
Combination of entry and middle marker (3)	Contact analogue behaviour (4)
Good preparation in case of successive manoeuvres (3)	Timing of animation (4)
No permanent display of visual content (2)	Pleasant (4)
	Outlines and transparency (4)
	Colouring (3)
	Static display of remaining distance (3)
	Good display of manoeuvres pointing straight (3)
	Enjoyable (2)
	Good preparation to next manoeuvre (2)
	Subtle display (2)
	Display in the primary FOV (2)
	Increases system trust (2)
	Roll-pitch compensation (2)
Intuitive (2) (8)	
Not distracting too much (2) (3)	

Table 29: Positive feedback for the concept variants in Field Study 2.

The participants of the study also gave negative feedback for both concepts. Again, there were statements mentioned in case of both concepts. A compilation of the given feedback is given in Table 30.

After driving with the *solid fishbone concept*, 14 subjects mentioned that they did not like the visualisation of a manoeuvre pointing straight and nine people mentioned that the zooming was disturbing. Six drivers complained about the fact that the visual elements are sometimes not visible at all and six subjects mentioned that the *solid fishbone concept* requires much attention while being distracting at the same time. Five subjects said that they are missing a navigation cue in roundabouts, three participants stated that the visual elements cover too much of the real environment, and two subjects did not like the design. Furthermore, two drivers each mentioned that *entry* and *middle marker* do not fit together and that the display is trembling. Finally, two subjects said that they are missing a continuous hint that tells the driver whether the system is still running without any problems.

In case of the *harpoon concept*, ten subjects mentioned that the static display of the remaining distance to the upcoming manoeuvre is too small and nine drivers stated that the roll-pitch compensation is disturbing. Further, seven participants mentioned that the integrated animation was distracting, three drivers found that the navigation cues are not dynamic enough, and three subjects said that the navigation hints are colliding with the static content. Two participants each stated that the animation starts too early and that manoeuvres get displayed too late. Lastly, two subjects stated that the readability and perceptibility of the visual content depends on the current weather conditions.

Again, there was feedback mentioned for both navigation concepts. The fact that the displayed visual content is too large and dominant was mentioned 13 times for the solid fishbones and three times for the *harpoon concept*. Furthermore, twelve participants stated that the visual content gets cut off after driving with the *solid fishbone concept*, whereas only three subjects said so after navigating with the *harpoon concept*. The timing of the navigation variant was rated poor, twelve times for the fishbones and four times for the harpoon variant. Eight participants stated that the positioning is inaccurate, after driving with the *solid fishbones concept* and two said so after driving with the *harpoon concept* and three drivers said that the fishbones are too bright, whereas only two were of this opinion in case of the harpoon variant.

<table>
<tr><th>Solid Fishbones Concept</th><th>Harpoon Concept</th></tr>
<tr><td>Visualisation of manoeuvre pointing straight (14)</td><td>Display of remaining distance too small (10)</td></tr>
<tr><td>Zooming (9)</td><td>Roll-pitch compensation disturbing (9)</td></tr>
<tr><td>Visual content sometimes not visible (6)</td><td>Animation distracting (7)</td></tr>
<tr><td>Requires a lot of attention and is distracting (6)</td><td>Cues not dynamic enough (3)</td></tr>
<tr><td>Navigation cue for roundabouts is missing (5)</td><td>AR content collides with static information (3)</td></tr>
<tr><td>Display is covering too much (3)</td><td>Animation too early (2)</td></tr>
<tr><td>Design (2)</td><td>Display of manoeuvres too late (2)</td></tr>
<tr><td>Entry and middle marker do not go together (2)</td><td>Visibility of display depends on current weather (2)</td></tr>
<tr><td>Display is trembling (2)</td><td></td></tr>
<tr><td>Permanent display is missing (2)</td><td></td></tr>
<tr><td colspan="2">Content too large and dominant (13) (3)</td></tr>
<tr><td colspan="2">Content gets cut off (12) (4)</td></tr>
<tr><td colspan="2">Timing (12) (4)</td></tr>
<tr><td colspan="2">Inaccurate positioning (8) (2)</td></tr>
<tr><td colspan="2">Too bright (3) (2)</td></tr>
</table>

Table 30: Negative feedback for the concept variants in Field Study 2.

Next, participants gave suggestions for improvement concerning both navigation concepts. A summary of the results is shown in Table 31.

In case of the *solid fishbone concept*, nine drivers suggested to add a suitable display for roundabouts, six subjects stated that the developers should reduce the size of the visual elements, and four participants voted for a smoother fade-in and -out of the visual elements. Three drivers each said that the timing of the display of the upcoming manoeuvre has to be improved and that the remaining distance to the current manoeuvre should be shown. Furthermore, it was mentioned two times each that the transparency of the shown elements could be adapted and that objects of the real world could be included in the navigation by being marked. Lastly, two participants each stated that the navigation hints could be illustrated in the shape of a cable or tube that drivers have to follow and that the *entry marker* should be displayed longer.

In case of the *harpoon concept*, five participants suggested that the single harpoon element should tilt in accordance with the curvature of the road. Four drivers each wanted an improvement of the animation's timing, an increasement of the transparency of the AR content and an improvement or removal of the roll-pitch compensation. Three drivers each suggested to enlarge the static visual content, to increase the opacity of the AR elements, and to add a separate cue for roundabouts. Also, two subjects stated that the display of outlines only should be matched better with the moment when drivers have to turn and two drivers said that making the animation more dynamic or *smoother* would be a meaningful improvement. Further, two subjects each said that manoeuvres that point straight should be indicated with the single harpoon element and not with a separate navigation cue and finally, it was mentioned two times that the visual elements should be less dominant or intrusive.

Solid Fishbones Concept	**Harpoon Concept**
Add display for roundabouts (9)	Tilt of harpoon element (5)
Make display more subtle (6)	Improve timing of animation (4)
Smoother fade-in and out of visual elements (4)	Improve fade-out behaviour (4)
Optimisation of positioning accuracy (3)	Improve or remove roll-pitch compensation (4)
Improve timing (3)	Adapt size of static displays (3)
Display is covering too much (3)	Increase opacity (3)
Show remaining distance to upcoming manoeuvre (3)	Add navigation cue for roundabouts (3)
Adapt transparency of visual elements (2)	Match outlines with turn-off point (2)
Include real objects by marking them (2)	Make animation more dynamic (2)
Include visual cable to follow (2)	Static harpoon in case of 'straight' manoeuvres (2)
Increase the display time of the entry marker (2)	Make display less dominant or intrusive (2)

Table 31: Suggestions for improvement for the concept variants in Field Study 2.

7.2.5.6 Final Survey

After driving with both navigation concepts, the participants had to answer additional questions.

The first question addressed the *harpoon concept's* dominant animation. The aim was to find out whether the subjects believed that this animation supports or disturbs them while navigating. Figure 51 gives an overview of the distribution of the votes.

In total, 18 subjects thought that the dominant animation of the *harpoon concept* supports them while navigating. Four subjects stated that they like the animation because it informs the driver punctually about when a manoeuvre can be expected and two subjects stated that with the integrated animation the driver knows precisely in which street he or she should turn. Other reasons mentioned once each were that the display of the distance remaining to the manoeuvre gets obsolete, that navigating gets more intuitive, and that the animation is easy to understand. Lastly, it was mentioned once each that the driver gets instant feedback on how his vehicle is standing in relation to the desired direction and that the animation visualises the upcoming steering movement.

One participant found that the dominant animation integrated into the *harpoon concept* was disturbing due to covering too much of the real-world environment.

Lastly, one subject did not want to make a decision. He or she stated that on the one hand, the animation supported on knowing in which street to turn and on the other hand, could distract the driver.

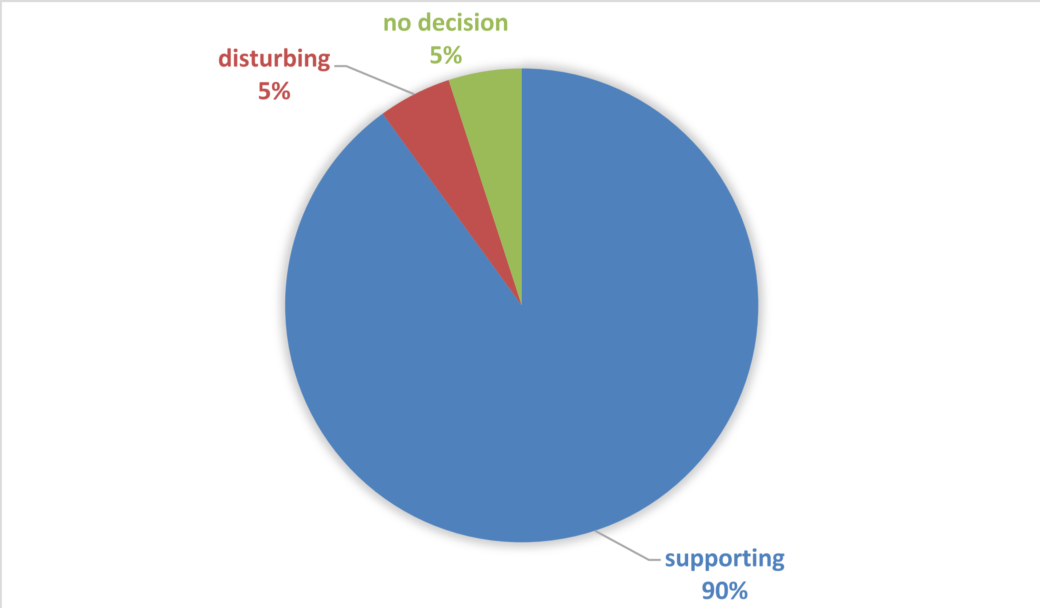


Figure 51: Distribution of subjects' answers regarding the question whether they found the distinct animation of the harpoon concept supporting or disturbing.

In the second question, participants were asked which concept they preferred and for what main reasons. Again, the given feedback was evaluated and assigned to suitable classes according to (Mayring, 2015), while Figure 52 shows the distribution of the votes

In total, 17 participants chose the *harpoon concept* and gave various reasons for doing so. In the following, only the statements mentioned at least twice are listed: Nine drivers chose the *harpoon concept* due to being less dominant and eight subjects stated that this variant has a better design. Further, it was mentioned three times that this navigation concept is more pleasant to use and two subjects found that it is better integrated into the real environment. Lastly, two participants each mentioned that they like the concept's permanent display of information that it is less intrusive and that positioning together with visibility are better.

Furthermore, two subjects voted for the *solid fishbone concept* and stated that this variant is less dominant, better designed, easier getting used to, and less distracting.

Finally, one participant could not make a decision. One the one hand, the driver mentioned that the *harpoon concept* was more pleasant just as target-oriented and on the other hand, the participant found that the solid fishbones were less distracting while driving.

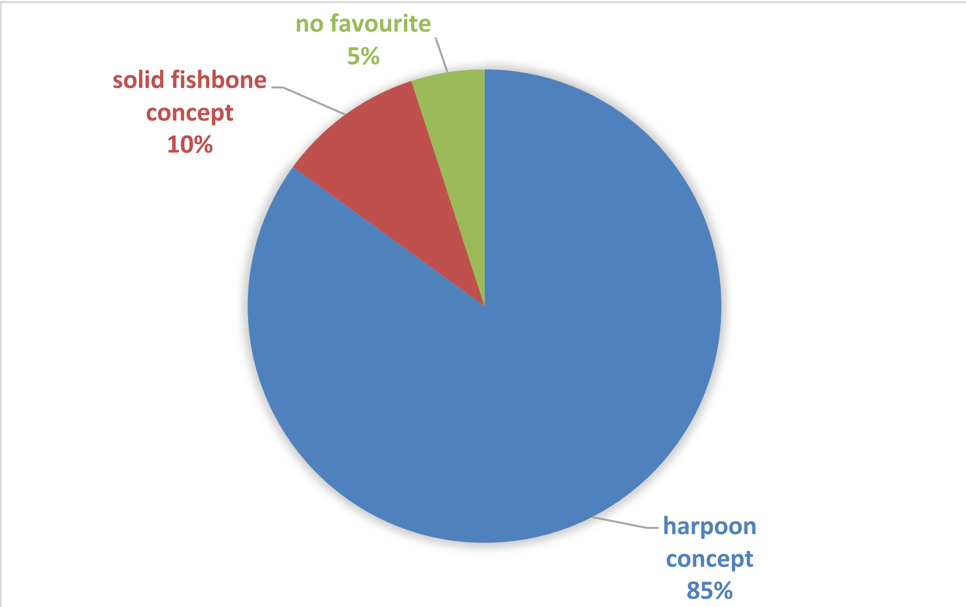


Figure 52: Distribution of subjects' answers regarding the question whether they prefer the harpoon concept or solid fishbone concept.

7.2.6 Discussion and Conclusion

In this field study, we compared the *solid fishbones concept* with a revised navigation concept, the so-called *harpoon concept*. This improved navigation variant is based on the findings of *Field Study 1*, which is described in Section 7.1. The experiment was conducted in the real traffic with a prototype car equipped with a complete AR HUD setup while drivers had to assess both concepts regarding various aspects (cf. *Research Question FS 2.1*).

Concerning navigation errors made, the findings show that the subjects on average made more navigation errors while driving with the *solid fishbone concept*. However, the difference was not significant and thus, H1: *Drivers make less navigation errors while using the harpoon concept* has to be rejected. Nevertheless, the findings show a strong tendency towards making fewer navigation errors while navigating with the help of the *harpoon concept*. A reason for this could be that the subjects rated the positioning of the visual content in the real world as significantly more accurate in case of the *harpoon concept*. This was mentioned in the open questions section as well. Also, participants complained in the open questions section that navigation hints are sometimes not visible in case of the *solid fishbone concept* and that visual content is cut-off strongly as well. Furthermore, it was criticised that in case of the fishbones, no navigation cue was visible in case of roundabouts and that the display for a manoeuvre hint pointing *straight* was confusing.

In terms of system trust, the results show a significantly higher system trust for the *harpoon concept* and thus, H2: *Drivers have a higher trust in the navigation with the harpoon concept* can be accepted. Reasons for the higher system trust could be that the position accuracy of the AR content was rated significantly higher in case of the *harpoon concept*. Furthermore, subjects mentioned in the open questions part that they liked the permanent display of the single harpoon element. Thus, drivers can see that the system is still running and that route guidance is active. Also, the subjects mentioned that the visual content of the *solid fishbone concept* is sometimes not visible or gets cut-off and that a navigation cue for roundabouts is missing. These problems could irritate the driver and lead to a lower system trust regarding the fishbones concept.

Further, significant differences could be found regarding mental workload that was measured with the DALI. The items *global attentional demand*, *visual demand*, *stress*, *temporal demand,* and the *global DALI score* showed significantly higher values in terms of the solid fishbones. Only in case of the item *perceived distraction*, the measured results did not show any significant difference. However, as the *global DALI score* is significantly higher for the *solid fishbone concept*, H3: *The drivers' subjective workload is lower for the harpoon concept* can be accepted. In case of the subjective assessment, the *harpoon concept* was rated as significantly less intrusive and covering, which could be reasons for a lower mental workload of the drivers. Further reasons for the results of the DALI could be that subjects rated the *harpoon concept* as easier to interpret, better positioned in the real world, and less demanding regarding concentration. Also, the subjects rated the masking effects caused by the *harpoon concept* as significantly less disturbing, which could be another reason for the lower mental workload. These results were supported in the open questions part as subjects complained that the fishbones are covering too much, require much attention, and distract the driver. Additionally, in case of the fishbones, more participants stated that the content of the *solid fishbone concept* is too large & dominant and that the positioning is inaccurate.

The self-created questionnaire containing questions with 6-point Likert scales and German school grades was designed to assess the given concepts regarding design, positioning accuracy, degree of masking, driver distraction, perception, and animation. The vast majority of the items showed significant differences and therefore, H4: *Drivers rate the harpoon concept better in terms of subjective assessment* can be accepted for the most part.

As the *harpoon concept's* animation was more dominant and complex, examiners wanted to investigate whether this might disturb drivers or give them support while navigating by leading their attention to the following turn-off point (cf. *Research Question FS 2.2*). The findings show that the participants had a positive stance toward the *harpoon concept*'s complex animation. In the subjective assessment, it was rated as significantly more supporting, more pleasant, and better designed than the animation of the *solid fishbone concept*. At the same time, drivers had a significantly lower mental workload while driving with the *harpoon concept*, which shows that drivers have no problems with processing the displayed animation and information. Further, when directly asked whether the more complex animation of the *harpoon concept* was supporting or disturbing while navigating, 90% of the participants stated that it supported them while driving. Reasons for this decision were among others that the driver gets informed punctually about when to expect a manoeuvre and that the turn-off direction can be recognised even faster with the help of this animation.

Some limitations have to be mentioned. The participants of this study were employees of *Daimler AG* but no experts in the field of AR HUD development. As this technology is not yet available in production vehicles, the subjects never used this system before and thus, their assessment of the technology could have been influenced by seeing it for the first time. Although, the order of the tested navigation concepts was counterbalanced to mitigate learning effects, using an AR HUD for the first time could still cause bias in results. This phenomenon will disappear with time when the AR HUD technology is available in production vehicles. Further, this study was conducted in the real traffic, which causes factors that cannot be controlled like different light or weather conditions and differences in traffic density.

In the future, developers will still have to deal with a variety of technical limitation, such as inaccurate sensor data or a limited FOV. However, the findings of this study show that the *harpoon concept* might be able to compensate these limitations better. Among others, participants rated the positioning accuracy of the *harpoon concept* as significantly better and had a higher trust in this concept. Also, the mental workload was lower in case of the *harpoon concept*.

However, to collect information on how to improve AR HUD navigation concepts even further, an open questions section was included (cf. *Research Question FS 2.3*). Like in *Field Study 1*, the findings of the open questions section comprise positive and negative feedback as well as suggestions for improvements. Further, the subjects were asked whether the more dominant animation of the *harpoon concept* was disturbing while navigating or not. Lastly, the subjects had to decide which navigation variant they preferred and for what main reasons.

Concerning the overall assessment, the *harpoon concept* was rated as better made and got a better all average grade than the fishbones. In the final survey part, when asked which concept they preferred, 85% of the subjects chose the *harpoon concept* for main reasons like being less dominant and better designed.

To put it into a nutshell, the results of the conducted field study show that the *harpoon concept* is more suitable as a navigation concept for AR HUDs. Among others, it got better ratings in terms of mental workload, system trust, design, positioning accuracy, degree of masking, and driver distraction. Also, drivers found the animation integrated into the *harpoon concept* supportive, which could be one of the reasons why less errors were made when using it. Now, the next step is to compare this improved AR HUD navigation concept to an already existing static navigation concept for HUD.

7.3 Field Study 3: Proof-of-Concept

In the experiment described in the following, we compared a contact analogue navigation with a conventional one. The *harpoon concept,* presented in Section 7.2.1, served as contact analogue navigation in an AR HUD. The aim of this field study was to find out how participants assess the contact analogue navigation with the still existing technical limitations compared to the already available conventional HUD navigation. Like in the previous field studies, no audio output was included.

7.3.1 Concepts Used in the Study

In this field study, the contact analogue *harpoon concept* is compared to a conventional HUD navigation.

In case of the *harpoon concept*, the static preview indication was removed as the aim of this study was to compare pure AR navigation with a conventional one. Otherwise, the participant would have static and contact analogue information when driving with the AR variant.

The conventional HUD navigation was based on the static preview indication of the *harpoon concept* examined in *Field Study 2* with minor changes. First, the position of the preview indication was determined to be on the left side of the HUD to avoid confusion. Furthermore, the size of the static indication was increased by factor 1.8 as some participants of Field *Study 2* could not recognise this information. This value was determined based on test drives with experts in the field of concept development for AR HUD. Figure 53 shows the conventional navigation used for this experiment.

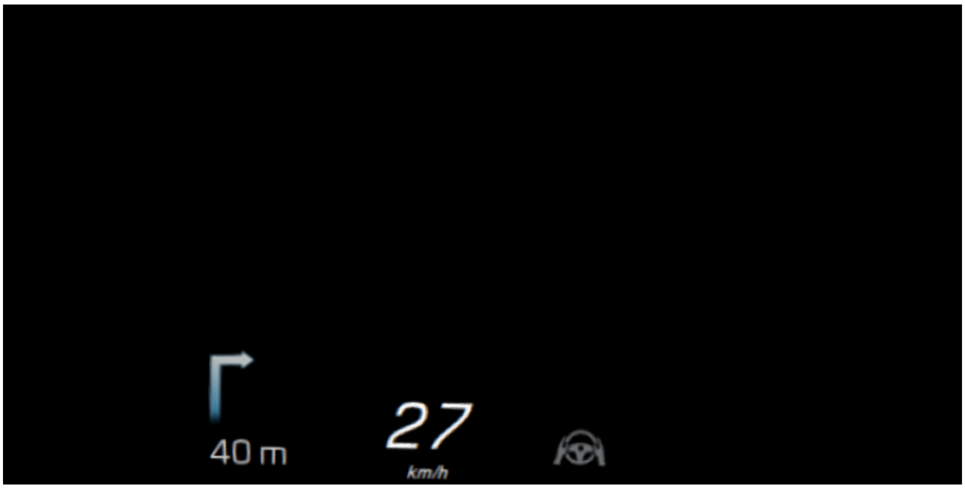


Figure 53: The conventional navigation used in Field Study 3.

In case of both navigation concepts, further information is shown in the HUD like it was done in the previous study in case of the *harpoon concept*. Firstly, the current vehicle speed is displayed, so that the participant does not have to avert the glance from the street to check this parameter. Secondly, a *Distronic* icon is displayed to simulate, together with the vehicle speed, further static information that is usually given in a HUD.

7.3.2 Hypotheses

This field study aimed to compare the developed *harpoon concept* with conventional navigation for HUD. There have been field studies in the past that compare those two navigation types (e.g. Pfannmueller (2017)), and it would be interesting to see how the results of this study compare to those.

It was important to assess whether it was easier for the participants to navigate with the new concept. This should be tested in terms of navigation errors (H1). Further, one wanted to find out whether the driver's trust in an AR HUD using the *harpoon concept* for showing navigation cues and in a conventional navigation system for HUD can be comparable. As the AR HUD technology was new for the participants that took part in the study, it was hypothesised that for now, people still trust the conventional version more (H2). Also, the subjective mental workload has been assessed in this experiment. Contact analogue navigation hints that match the real-world environment might increase the driver's workload as humans try to separate real from imagined (Edgar, 2007). Thus, the perceived workload is expected to be higher for the AR HUD navigation (H3). Further, the participants had to give a subjective concept assessment with regard to *design*, *colour*, *comprehensibility*, *perceptibility*, and *driver distraction*. Besides, drivers had to make a total assessment of the concepts, together with German school grades (H4). It was hypothesised that subjects rate the contact analogue navigation concept significantly better than the conventional one due to its novelty and engaging nature. Especially when one experiences world-fixed navigation in an AR HUD for the first time.

The defined hypotheses are listed below:

- H1: *Drivers make less navigation errors while using the harpoon concept.*
- H2: *Drivers have a higher trust in the conventional HUD navigation system.*
- H3: *The drivers' subjective workload is higher while using the harpoon concept.*
- H4: *Drivers rate the harpoon concept better in terms of subjective assessment*.

7.3.3 Apparatus and Experimental Setup

In this section, the apparatus and experimental setup are described. The test vehicle, test environment, and test track are the same as in *Field Study 1* and *2* and are explained in Section 7.1.5.

7.3.3.1 Participants

In total, 26 participants took part in this field study while we had to remove datasets of 2 subjects due to technical problems. All of the remaining 24 participants of this in-the-wild on-road study were employees of *Daimler AG.*

From the remaining 24 participants, 6 were female and 18 were male, ranging in height from 1.64 meters to 1.93 meters with M = 1.79 meters and SD = 0.08. Their age ranged from 25 to 62 years with M = 35.50 and SD = 10.13 and all participants were holding a valid driving license (category B). The longest length of the driver's license possession was 49 years, whereas the shortest was 7 year with M = 17.79 and SD = 10.32. Further, 4 subjects had a driving license for motorcycles (category A). The average amount of the approximate number of driven kilometres in the last twelve months was 15291.67 with a standard deviation of 7543.95. All participants were normal sighted or wore glasses or contact lenses for sight correction.

All subjects had experience with conventional navigation solutions installed on a smartphone or integrated into a vehicle and the majority of the drivers used them regularly (cf. Figure 54). Three of the participants have never used a static HUD before and none of the drivers has a HUD in his private car. The majority of the participants had a positive attitude towards HUDs in general (cf. Figure 55). Furthermore, every participant has completed a special driving safety training organised by *Daimler AG* to be allowed to drive the test vehicle used for this field study. All participants were tested individually and gave their written consent to participate in the experiment.

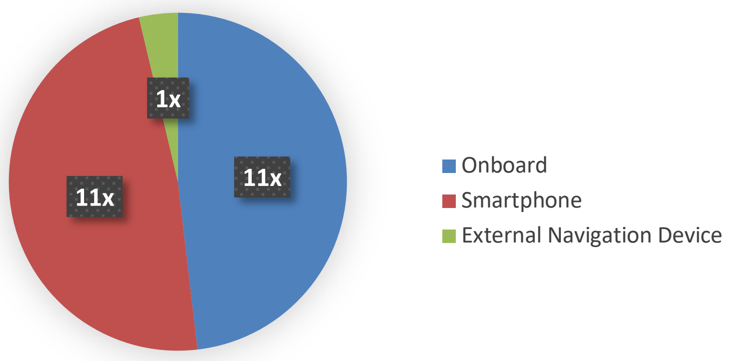


Figure 54: Distribution of subjects' answers regarding what kind of navigation systems they use.

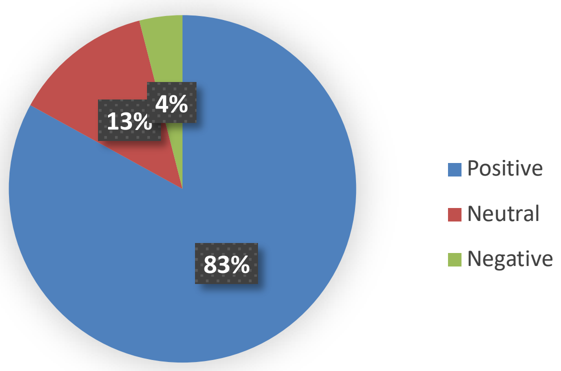


Figure 55: The participants' attitude towards HUDs in general.

7.3.3.2 Questionnaires

In this section, the questionnaires used during the study are introduced. The DALI for measuring subjective mental workload has already been used in previous studies and is described under 7.1.5.5. The *Trust Scale* for measuring the trust of users in a current system has been used already as well and is explained under 7.2.4.2. Furthermore, a questionnaire for subjective assessment regarding *design*, *colour*, *comprehensibility*, *perceptibility*, and *driver distraction* will be introduced. Additionally, an overview of the open questions asked to the participants is given. Finally, drivers had to compare both navigation concepts in terms of animation and general assessment in a final survey.

<u>Questionnaire for the subjective evaluation of AR HUD navigation concepts</u>

This self-designed questionnaire used in the experiment is used to compare the examined navigation concepts with respect to *design*, *colour*, *comprehensibility*, *perceptibility*, and *driver distraction*. Furthermore, the participants can make a total assessment of the concepts and assign German school grades (1 = *best*, 6 = *worst*). The seven items, but the questions with the school grades, used a 7-point Likert scale with the endpoints *strongly disagree* (value = -3) and *strongly agree* (value = 3) as well as *extremely unpleasant* (value = -3) and *extremely pleasant* (value = 3) while the order of the word pairs was alternating to keep the participants' attention. A 7-point Likert scale was used to give the participants the possibility to have a neutral opinion in case of agreement with the corresponding concept characteristic.

In case of the navigation concept for AR HUD, the *harpoon concept*, seven additional questions were added to the questionnaire, again using 7-point Likert scales with the endpoints mentioned above. The aim was to get further information concerning masking caused by visual content. Participants were asked whether they found the masking of real objects disturbing and whether too much was covered. Further, subjects were asked if the visual information distracted them from the actual driving task and if the AR HUD met their expectations. Next, drivers had to state whether they found the inaccurate positioning of the AR content disturbing, whether navigation with the AR HUD gave them a sense of security, and whether they felt comfortable while navigating with the AR HUD.

Both questionnaires, for AR HUD and conventional HUD navigation, can be found in Appendix E.2.

Open Questions

After each drive, participants had to state what they liked or disliked about the corresponding concept. Furthermore, they had to give suggestions for improvements concerning the current navigation concept together with additional comments. The corresponding questionnaires can be found in Appendix E.3.

Final Survey

After the participants had seen both concepts, they had to answer a few final questions. The self-designed questionnaire consisted of four items. The first two questions used a 7-point Likert scale with the endpoints *strongly disagree* (value = -3) and *strongly agree* (value = 3) while the order of the endpoints was alternating to make sure that the subjects stayed focused while answering. The first item asks the participant whether he or she thinks that the display of driving-related information on the windshield makes sense in general. The second item contains the question of whether the AR HUD is a meaningful advancement of the conventional HUD. Item three and four were open questions, whereby item three was included to ask the driver whether the *harpoon concept's* dominant animation could be seen as support while navigating together with giving reasons for the corresponding answer. Item four consists of the questions concerning which navigation concept was preferred and why.

7.3.3.3 Procedure

The procedure of this field study was similar to the previous field studies described in Section 7.1 and 7.2 with changes.

After getting a short introduction to the prototype vehicle, the participants were allowed to adjust the positions of the driver seat, interior and exterior mirrors, as well as air conditioning to their comfort needs. DASs like LDP and BSM were available in the car. Also, in this study, the usage of ACC was not allowed, as this might have had an influence on the driver's workload.

Next, the participants calibrated the HUD according to the current head position and took a short practice route to get accustomed to the test vehicle. Further, the current trajectory of the steering angle was shown in the AR HUD to get a first impression of the system (cf. Figure 48 in Section 7.2.4.3). This functionality was added as the subjects of this study were no experts in fields related to AR HUD development. After stopping at a parking area close to the test track, a consent form was filled and three test pictures were shown in the AR HUD (cf. Figure 33 in Section 7.1.5.6).

While the examiner started the test software, the subjects filled a questionnaire covering demographical data, driving experience, and experience with HUDs in general. The investigator logged the current weather conditions. Next, the participants were given instructions for the study and were told to think aloud during the drives. Every subject had to drive the test route two times with an identical test procedure for both HUD navigation variants. Half of the drivers started with the navigation for conventional HUD and the other half with the *harpoon concept* to compensate learning effects concerning the test track. The experimenter sat on the passenger seat next to the driver while a second person was sitting on the rear bench behind the examiner to log incidents like traffic blocks, system malfunctions, and navigation errors. Additionally, a *GoPro dashcam* was mounted above the head-unit of the prototype vehicle to record a video from each drive together with audio data. If subjects were insecure about interpreting the navigational hints, they were asked to tell the examiner in which direction the cue points. This was done to avoid possible inconsistencies caused by rerouting.

After finishing the test track, the subjects filled in the DALI, a tool designed to evaluate the driver's mental workload. Also, they had to fill the *Trust Scale* that was developed to measure trust between people and automated systems. In addition, a self-designed questionnaire to assess different aspects of each concept (*design*, *colour*, *comprehensibility*, *perceptibility*, and *driver distraction)* was given to the subjects. Finally, participants had to answer open questions in which they should answer what they liked and disliked about the shown concept and what suggestions for improvements they would have.

7.3.3.4 Statistical Methods

The *Trust Scale* means for each navigation concept were compared using a *Wilcoxon signed-rank test*. In case of the DALI, mean scores and single item means were compared. The self-designed questionnaire was evaluated based on single item mean comparisons as well. *Wilcoxon signed-rank tests* were conducted for questionnaire and navigation error data which was not normally distributed. The second part of the evaluation comprised to test for order effects with the same methods. The *alpha level* for all evaluations was set to .05 and statistical tests were conducted using the software *SPSS* (Version 24.0).

7.3.4 Results

This section contains a compilation of the study results, including a descriptive analysis of the navigation errors made by the subjects. Further, the outcomes of the inferential analysis of the standardized questionnaires *Trust Scale*, DALI, and the questionnaire for subjective assessment is shown. Lastly, this section contains an overview of the feedback that the experts gave in open questions. Anna Bruder supported the data analysis while doing an internship at *Daimler AG*.

7.3.4.1 Navigation Errors

28 navigation errors were recorded in total. Most of them happened at four points on the test track [*manoeuvre 1* (7 errors, 25%), *manoeuvre 5* (5 errors, 17.86%), *manoeuvre 8* (6 errors, 21.43%), and *manoeuvre 16* (5 errors, 17.86%)]. A quarter of all navigation errors were made at *point 1*, the very first manoeuvre on the route. Six errors (21.43 %) were recorded at *point 2* and lastly, five navigation errors (17.86%) were made at each of the *points 3* and *4*. The total number of manoeuvres in the test track is 20. There is a difference between the average navigation error

made per subject with the AR HUD ($M = 0.42$, $SD = 0.78$) and the conventional ($M = 0.75$, $SD = 0.74$) navigation concept. However, that difference turned out to be non-significant ($Z = -1.37$, $p = .09$). Further analysis regarding order effects revealed that there is no significant difference between the first ($M = 0.67$, $SD = 0.82$) and the second time ($M = 0.5$, $SD = 0.78$) participants followed the route ($Z = -0.6$, $p = .55$).

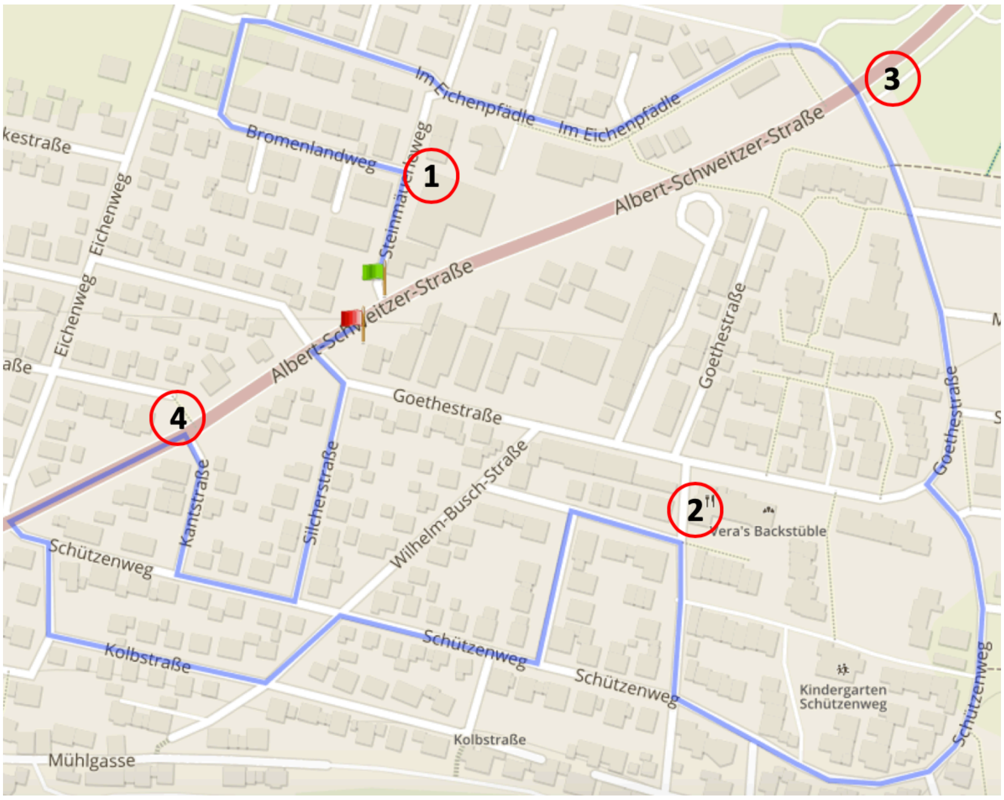


Figure 56: Turn-off points with frequent occurrence of navigation errors for Field Study 3.

7.3.4.2 Trust Scale

A detailed description of the *Trust Scale* questionnaire can be found in Section 7.2.4.2. Mean *Trust Scale* results were quite similar for both, the AR HUD navigation concept ($M = 5.67$, $SD = 0.95$) and the conventional navigation concept ($M = 5.52$, $SD = 0.94$). Statistical analysis revealed that there is no significant difference between *trust scores* for the two concepts ($Z = -0.36$, $p = .36$). We found no significant order effects either.

7.3.4.3 Driving Activity Load Index (DALI)

The DALI is elaborated in Section 7.1.5.5. Figure 57 shows the mean values of the single items as well as the global score of the DALI for each concept.

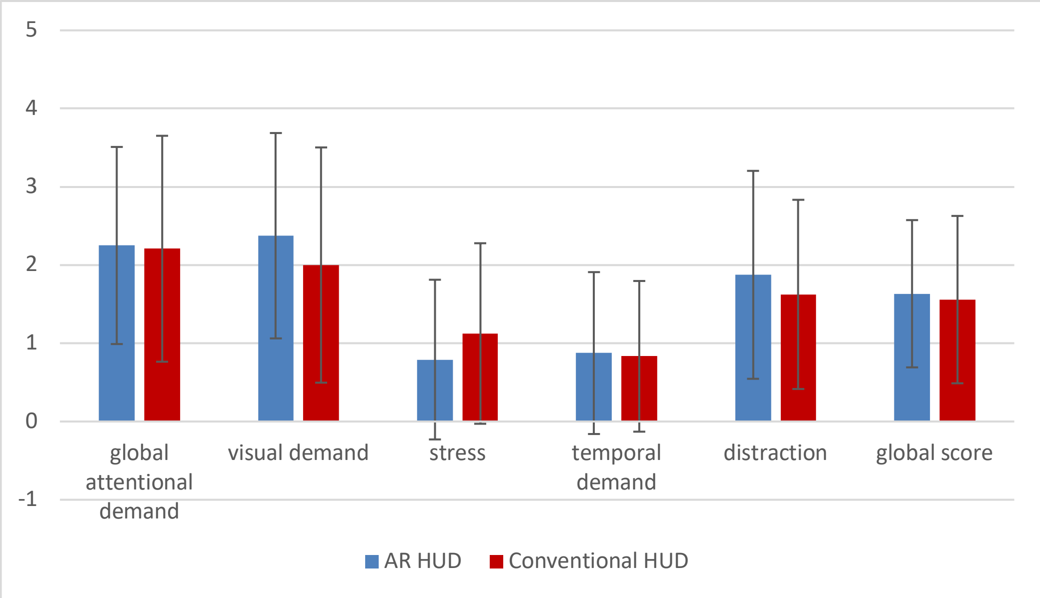


Figure 57: Mean scores (error bars: SD) of DALI for the AR HUD and the conventional navigation system.

None of the differences turned out to be significant (*global attentional demand*, $Z = -0.17$, $p = .43$; *visual demand*, $Z = -1.05$, $p = .15$; *stress*, $Z = -1.41$, $p = .08$; *temporal demand*, $Z = -0.18$, $p = .43$; *distraction*, $Z = -0.8$, $p = .21$; and *global score*, $Z = -0.34$, $p = .37$). However, there is a slight trend for the visual demand of the AR HUD navigation concept ($M = 2.38$, $SD = 1.31$) to be higher than of the conventional navigation concept ($M = 2.0$, $SD = 1.5$). Furthermore, a trend can be seen for the stress scale. Subjects rated their perceived stress lower when using the AR HUD navigation concept ($M = 0.79$, $SD = 1.02$) than when using the conventional navigation system ($M = 1.13$, $SD = 1.15$). The subsequent order effect analysis showed that the *global attentional demand*, the *visual demand*, the *distraction*, as well as the *global score* were significantly lower for whatever concept subjects used during the second drive (cf. Table 32).

Category	M (1st concept)	M (2nd concept)	Z	p
Global attentional demand	2.58	1.88	-2.03	< .05
Visual demand	2.67	1.71	-2.81	< .01
Stress	1.17	0.75	-1.63	.1
Temporal demand	0.88	0.83	0	1
Distraction	2.08	1.42	-2.19	< .05
Global score	1.88	1.32	-2.81	< .01

Table 32: Mean values of DALI categories for the first and second concept subjects used.

7.3.4.4 Questionnaire for Subjective Assessment

The questionnaire for subjective assessment (cf. Section 7.3.3.2) consists of seven items regarding *design*, *positioning*, *perception*, and *animation* as well as two *overall rating* items. Additionally, there were seven items assessing *masking*, *distraction*, and *positioning* for the AR HUD navigation concept only. Apart from one item where participants were asked to rate each concept as a whole using German school grades from 1 (*best*) to 6 (*worst*), all items are 7-point Likert scales.

No.	Statement	M (AR HUD)	M (conventional)	Z	p
1	*I thought the design of the navigation concept was appealing.*	1.75	- 0.79	- 3.87	< .001
13	*I think the navigation concept as a whole is well-made.*	1.83	0.42	- 3.56	< .001
14	*Please rate the navigation concept using German school grades.*	2.04	2.75	- 3.04	< .01

Table 33: Mean values of significant results. Rating scales for items 1 and 13 ranging from -3 (strongly disagree) to 3 (strongly agree).

Table 33 summarises the significant results only. Subjects perceived the design of the AR HUD navigation concept as much more appealing than the design of the conventional navigation concept and rated it higher in terms of how well it is made. Also, they graded the AR HUD navigation concept with a 2.04, which translates to '*good*' whereas the conventional navigation concept was given a significantly lower grade of 2.75, translating to '*satisfactory*'. Order effect analysis revealed that subjects thought they needed to concentrate significantly less the second time they drove around the test track (M = 0, SD = 1.67) compared to the first time (M = -1.0, SD = 1.75), Z = - 2.12, p < .5.

Table 34 shows the results of the items for assessing the AR HUD only, whereas the endpoints for question six till eleven were *strongly disagree* (value = -3) and *strongly agree* (value = 3). For question number twelve the endpoints were *very unpleasant* (value = -3) and *very pleasant* (value = 3). Figure 58 and 59 clarify the results with the help of bar graphs.

No.	Statement	M (AR HUD)	SD (AR HUD)
6	*I thought the masking of the real world was disturbing.*	-1.83	1.49
7	*In my opinion, the concept was covering too much of the real world.*	-1.83	1.69
8	*The AR HUD navigation concept distracted me from the driving task.*	-1.42	1.35
9	*The built-in AR HUD fulfilled my expectations.*	0.96	1.76
10	*The sometimes-inaccurate positioning of the AR HUD content disturbed me.*	0.67	1.86
11	*Navigating with the AR HUD gave me a feeling of security.*	1.38	1.01
12	*Overall, navigating with the AR HUD was…*	1.04	1.71

Table 34: Mean values of AR HUD assessment. Rating scales range from -3 till 3. Endpoints for item 6 till 11 are strongly disagree and strongly agree. Endpoints for item 12 are very unpleasant and very pleasant.

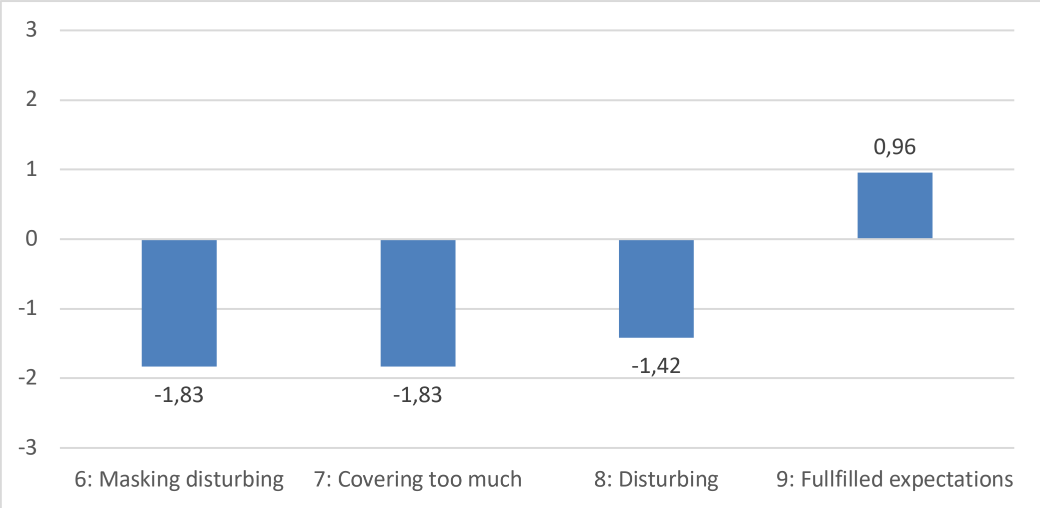


Figure 58: Part one of mean values of AR HUD assessment as bar graphs. The endpoints for item 6 till 9 are strongly disagree and strongly agree.

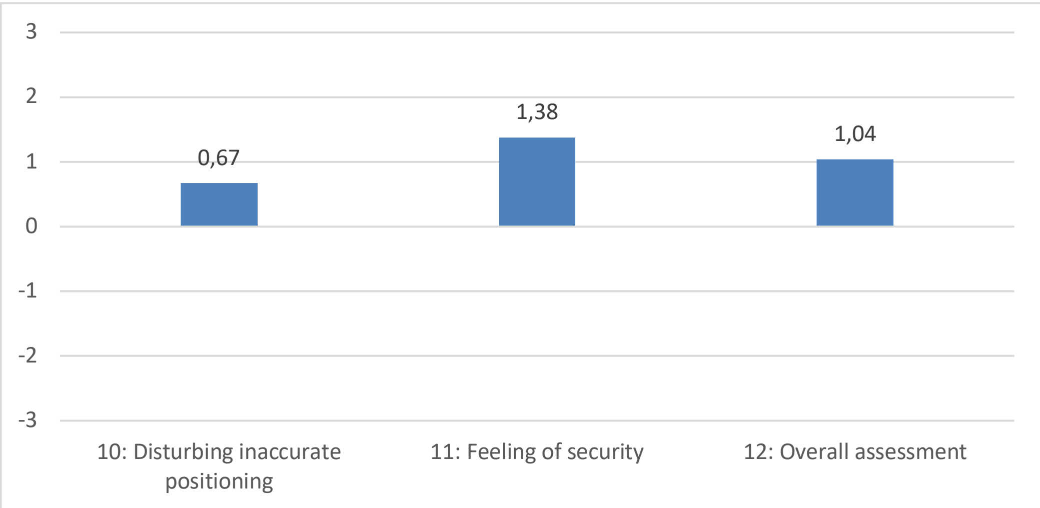


Figure 59: Part two of mean values of AR HUD assessment as bar graphs. Endpoints for item 10 till 11 are strongly disagree and strongly agree. Endpoints for item 12 are very unpleasant and very pleasant.

7.3.4.5 Open Questions and Think Aloud

In addition to the DALI, *Trust Scale* and a self-designed questionnaire, the subjects had to answer a couple of open questions after every drive. These included questions about what drivers liked or disliked about each navigation variant and what suggestions for improvement they would make. Furthermore, they had to think aloud and tell what they liked or disliked about the navigation concepts and what they would improve. There was feedback that was only given by one participant. Those individual comments are not mentioned in this section as they would go beyond the scope, but can be looked up in the corresponding table included in Digital Appendix.

The analysis of the open questions and the thinking aloud has been conducted according to the *qualitative content analysis* by Mayring & Fenzl (2014) that is based on the inductive development of categories. Feedback which participants mentioned during both, thinking aloud and open questions, has only be counted once.

Concerning the *AR navigation*, an overview of the positive feedback the participants gave, can be looked up in Table 35. Eight subjects appreciated that the distance to the upcoming turn-off point was shown by the adaption of the fishbones' size and liked the resulting depth perception. Furthermore, eight subjects shared the opinion that the AR concept's animation was easy to understand, well made, pleasant, and well-timed. Five participants mentioned that they appreciated the fading out animation of the fishbones and four drivers believed that the navigation concept for AR HUD was exciting and thus, caused a 'wow-effect' for them. Three subjects each found that the display was subtle, that the navigation variant was innovative, and that the concept prepared them well for manoeuvres being immediately successive. Two participants each appreciated that the AR navigation hints were structured clearly and that, in comparison to the conventional navigation, they were not as passive and also easier to understand. Further, two participants believed that the concept was visually appealing and two participants liked the conciseness of the shown virtual information when approaching a turn-off point. Finally, two more subjects stated that they liked the good integration of the visual concept into the real-world environment.

In case of the *conventional navigation*, seven subjects liked that there was a textual display giving information on the remaining distance to the upcoming manoeuvre and five participants stated that this navigation concept was simple and clear. Also, four drivers mentioned that this navigation variant is rather common, so people are familiar with it and know how to use it. Two subjects each appreciated the good timing, the non-disturbing and calm display of virtual information, as well as the fact that the system behaviour is predictable.

Further, there was feedback that was mentioned for *both concepts*. In case of the *AR navigation* concept, eight subjects found that it was intuitive and easy to interpret, whereas only four subjects thought so for the conventional navigation concept. Four subjects appreciated the conventional navigation's contrast and three participants had this impression in case of the AR concept. Four participants stated that it was easier for them to focus on traffic because the conventional navigation concept did not really distract them and three drivers mentioned this fact in case of the AR variant. After driving with the AR concept, four subjects mentioned that they experienced only little masking effects, whereas only two participants said that in case of the conventional one. Two subjects stated that the distance information included in the conventional navigation which was shown permanently gave them a feeling of security. Three drivers mentioned this in case of the AR navigation. In case of both concepts, two drivers liked the size of the displayed content.

AR navigation	Conventional HUD navigation
Depth perception (8)	Display of manoeuvre distance (7)
Animation was intuitive, well-made, pleasant, and well timed (8)	Simple and clear (5)
Fading out animation of fishbones (5)	Familiar (4)
'Wow effect' while using concept (4)	Timing (2)
Subtle display (3)	Non-disturbing and calm (2)
Good preparation in case of successive manoeuvres (3)	Predictable (2)
Clear structure (2)	
Not as passive as conventional concept (2)	
Easier to understand than conventional (2)	
Visually appealing (2)	
Concise (2)	
Integration of concept into real world (2)	
Intuitive (8) (4)	
Good contrast (3) (4)	
Not distracting (3) (4)	
Only little masking effects (4) (2)	
Permanent information gives a feeling of safety (3) (2)	
Size of virtual content (2) (2)	

Table 35: Positive feedback for the concept variants in Field Study 3.

In terms of what participants did not like about the *AR navigation*, an overview is given in Table 36. More than half (13) of them mentioned the bad visualisation of the navigation hint *straight*. Further, ten drivers criticised the vertical movement along the z-axis, the *roll pitch compensation* of the harpoon. Nine subjects disliked the fact that visual content was cut off or left the FOV. Further, the flickering of the display was criticised six times and the collision of the contact analogue content with the static information was mentioned five times. Three drivers believed that the shown arrows were too large. Two subjects each stated that the distance to the upcoming turn-off point was missing and that the visual content looked strange in case of road gradients.

For the *conventional navigation,* the subjects gave negative feedback as well. One point of criticism which was mentioned by 16 participants was that the remaining distance was difficult to estimate or not precise enough and three drivers stated that they made navigation errors because of this reason. Eight participants had the impression that this navigation concept was old fashioned, boring, and non-appealing. Further issues that were stated were that the displayed navigation information was not detailed enough (eight) and too small (five). Four subjects criticised that there was no hint concerning the manoeuvre that followed the current one, especially in case of many turn-offs necessary in a short time. Three participants mentioned that the virtual information was too low in contrast. Other problems mentioned by two participants each were that the navigational information was not intuitive, not intelligent, too static, and that they did not like the colour scheme.

Also, in case of negative feedback, there were issues mentioned for both concepts. Ten participants stated that they disliked the, at times, inaccurate positioning of the AR content, whereas only two mentioned that while driving with the conventional navigation. Three drivers believed that the visibility of the visual content was bad or the contrast was too low in case of both concepts. Two participants complained about the bad timing of the AR navigation's elements and one subject had this impression in case of the conventional variant. Finally, two participants felt like they needed to concentrate more when navigating with the AR variant, whereas the same issue was mentioned two times in case of the conventional concept.

AR navigation	Conventional HUD navigation
Visualisation of 'straight' (13)	Inaccurate distance indication (16)
Roll-pitch compensation (10)	Old-fashioned, boring, and non-appealing (8)
Cutting of virtual content (9)	Not detailed enough (8)
Flickering of display (6)	Too small (5)
Collision of static and contact analogue content (5)	No information to next manoeuvre (4)
Arrows too large (3)	Too low in contrast (3)
Distance to manoeuvre missing (2)	Not intuitive (2)
Visual content in case of road gradients (2)	Not intelligent (2)
	Too static (2)
	Colour scheme (2)
Inaccurate positioning (10) (2)	
Bad visibility and low contrast (3) (3)	
Bad timing (2) (1)	
Higher level of concentration required (2) (2)	

Table 36: Negative feedback for the concept variants in Field Study 3.

In the next part of the interview, the participants were asked to give suggestions for improvement. Table 37 provides an overview of the results. In case of the *AR navigation*, eleven drivers suggested adding visual or textual hints concerning the remaining distance to the upcoming manoeuvre. Five subjects thought that a different visualisation of roundabouts is necessary. Also, drivers suggested to reduce size or dominance of the displayed visual information (four) and had the idea to add a tilt of the harpoon element, e.g. to clarify elongated curves (four). Ideas stated by three participants each were the reduction of the number of fishbones used, the improvement or removal of the *roll pitch compensation*, and either the reduction of the harpoon size or the hiding of the element in case of longer road sections without manoeuvres. Showing the navigation content additionally in head-unit or IC, coupling vehicle and animation speed, bending the fishbones in curves, and integrating a special display in case of immediately consecutive manoeuvres were suggestions stated by two drivers each. Lastly, two subjects asked for an additional auditory cue in case of complex traffic situations and two drivers voted for an adaption of colour scheme or contrast depending upon the current weather conditions.

In case of the *conventional navigation*, eight subjects suggested to create a more differentiated and detailed display of manoeuvres ahead and six participants wished that the shown visualisation should be more prominent. Three drivers each stated that they would appreciate it to have an additional map section in the HUD and that information on the manoeuvre following the current one should be added. Two drivers wanted the concept to be more interactive and dynamic. To increase the contrast, to design the concept elements in a more modern way, and to make it visually more appealing was suggested by two participants each.

AR navigation	Conventional HUD navigation
Hints for remaining distance (11)	More detailed display of manoeuvres (8)
Different visualisation for roundabouts (5)	Increase size of shown content (6)
Reduce size of displayed information (4)	Display small map section in HUD (3)
Add tilt of harpoon (4)	Add information on the manoeuvre following the current one (3)
Reduce number of fishbones (3)	Make concept more interactive and dynamic (2)
Improve or remove roll-pitch compensation (3)	Increase contrast (2)
Reduce harpoon size or hide it situational (3)	Make design more modern (2)
Show content in IC and head-unit as well (2)	Make concept visually more appealing (2)
Couple vehicle speed and animation (2)	
Bed fishbones in curves (2)	
Special display for turns being immediately consecutive (2)	
Additional auditory hints for complex situations (2)	
Adapt colour or contrast depending on weather conditions (2)	

Table 37: Suggestions for improvement in Field Study 3.

7.3.4.6 Final Survey

After having completed both of the drives, the subjects had to answer two additional questions. First, they had to answer two questions, using a 7-point

Likert scale, regarding the usefulness of the AR HUD technology. The participants agreed that the advancement of the conventional HUD by the integration of AR as well as the display of driving-related content in the windshield are meaningful advancements in the field of ADAS. An overview of the results is given in Table 38:

Statement	Mean ± SD
In my opinion, the display of content on the windshield that is relevant for driving is useful.	2.83 ± 0.48
The AR HUD is a useful advancement of the HUD	2.33 ± 1.2

Table 38: Mean values (± SD) of the two final survey questions utilising a Likert scale. Rating scales ranging from -3 (strongly disagree) to 3 (strongly agree).

Second, the subjects had to give their opinion on whether the dominant animation of the AR HUD concept was supporting or disturbing them and for what reasons. Figure 60 shows the distribution of the votes given while it was only possible to evaluate the feedback from 20 of 24 subjects. Eighteen participants stated that the animation helped them while navigating with the navigation concept for AR HUD. The reasons mentioned were that the contact analogue behaviour of the fishbones showed them the exact moment when they had to make a turn (four mentions). Further, two participants mentioned that the concept with the dominant animation required fewer attention and therefore is less distracting and also the animation's intuitiveness was mentioned two times. Two participants gave negative feedback concerning the dominant animation of the AR navigation. One driver found that the animation is to slow and takes too long until the current turn direction is shown. The other one mentioned that the whole system is still too inaccurate and thus, also the animation is confusing.

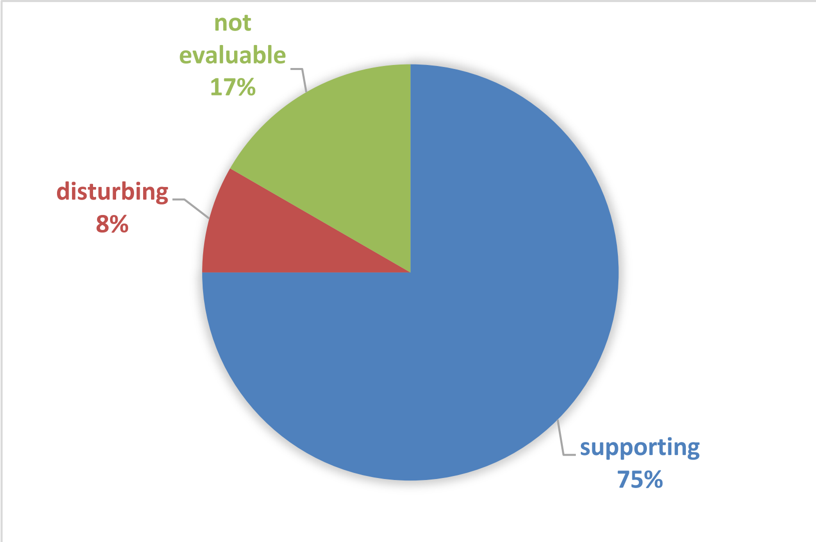


Figure 60: Distribution of subjects' answers regarding the question whether they found the distinct animation of the AR navigation rather supporting or disturbing.

Finally, the participants had to state which concept they favoured and for what main reasons. Figure 61 shows the distribution of the given votes. Twenty subjects favoured the *AR HUD navigation*. Main reasons that were given by at least two subjects each were: the navigation cues given by the AR HUD concept were more accurate (seven mentions), more intuitive (two mentions), not distracting (two mentions), and did not require a lot of mental resources (two mentions). Besides, it was mentioned that the navigation concept for AR HUD worked better for immediately consecutive manoeuvres (two mentions) and was easier to perceive (two mentions). Only one subject preferred the conventional navigation because of its reduction to what is necessary. Three participants did not have a preferred concept and voted for a combination of both variants.

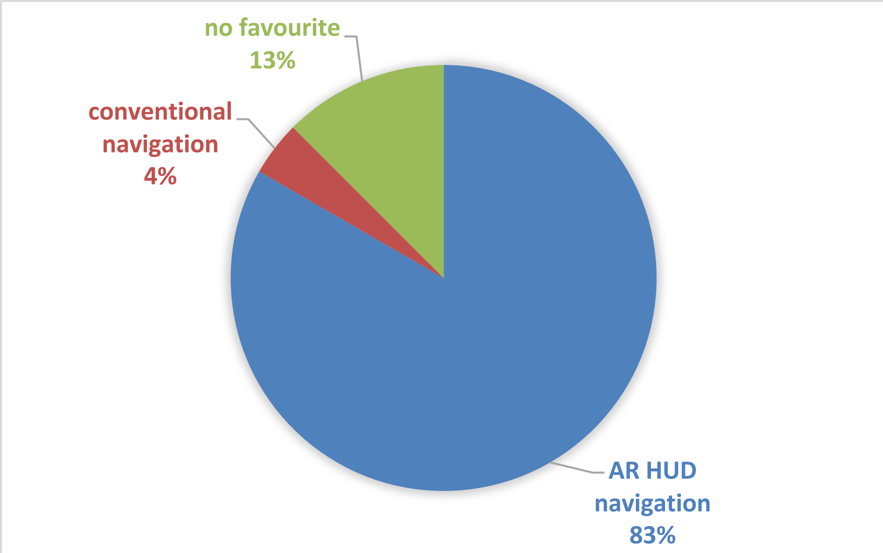


Figure 61: Distribution of subjects' answers regarding the question whether they prefer the AR HUD navigation or the conventional one.

7.3.5 Discussion and Conclusion

In the field study presented above, we compared a conventional HUD navigation to a contact analogue one while the subjects had to assess both concepts regarding various measures (cf. *Research Question FS 3.1*). Furthermore, the subjects had to state whether a contact analogue navigation concept is an improvement compared to the conventional HUD navigation despite still existing technical limitations (cf. *Research Question FS 3.2*). As contact analogue navigation concept, we used the *harpoon concept*, which was developed in this thesis. The study was conducted in the real traffic with a prototype car equipped with a complete AR HUD setup.

In case of navigation errors made while driving, the findings did not show significant differences between HUD and AR HUD. Thus, H1: *Drivers make less navigation errors while using the harpoon concept* cannot be accepted. However, the results showed a strong tendency towards making less navigation errors with the AR HUD, although the participants drove with this technology for the first time. This indicates that subjects were able to adapt to the AR HUD quickly. This outcome aligns with results from Bauerfeind et al. (2019), Israel (2013), Pfannmueller (2017), and Voehringer-Kuhnt (2015) that also observed less navigation errors in case of an AR HUD compared to a conventional one.

Regarding system trust, both HUD variants were rated almost the same and thus, H2: *Drivers have a higher trust in the conventional HUD navigation system* has to be rejected. This result supports the AR HUD as it indicates that drivers trust this technology quickly, although they used it for the first time. However, developers still have to deal with some technical limitations regarding the AR HUD technology like an inaccurate sensor or GPS data. Therefore, researchers have to investigate the behaviour in case of wrong navigation hints that might lead to dangerous driving situations when they, e.g. point into the oncoming traffic.

Furthermore, the subjective mental workload was measured for both HUD types, while the findings do not show a significant difference regarding the global score of the DALI. Thus, H3: *The drivers' subjective workload is higher while using the harpoon concept* has to be rejected. Also, Pfannmueller (2017) could not measure significant differences regarding mental workload when comparing HUD and AR HUD navigation in the field. This outcome speaks for the AR HUD technology, as it indicates that the drivers were not overstrained by the system, although they used it for the first time. For the item *visual demand*, however, the results showed slightly higher values in case of the AR HUD which could be traced back to the fact that participants had to process the dominant animation of the *harpoon concept*. Also, the technical problems mentioned, like the cut of the visual content, the inaccurate roll-pitch compensation, or the collision of static and contact analogue elements, could be a reason for higher visual demand. Furthermore, the results showed a slightly higher value for the conventional HUD in terms of *stress*. A reason for this could be the inaccurate display of the remaining distance to the upcoming turn-off point, which was mentioned by some participants.

The questionnaire for subjective assessment contained seven items to compare both HUD types regarding *design*, *positioning*, *perception*, *animation*, and *overall rating*. The findings show that the AR HUD was preferred especially regarding *design* and *overall rating*. For the remaining items, the differences were not significant. Thus, H4: *Drivers rate the harpoon concept better in terms of subjective assessment* can only be accepted partly. Further, the participants had to assess the AR HUD concept in terms of *masking*, *distraction*, and *positioning*. The findings show that participants rated the masking of the real-world environment as not critical or disturbing. Also, the driver distraction was assessed as rather low. The only thing that was still a bit disturbing was the sometimes-inaccurate positioning of the visual elements displayed in the AR HUD.

After driving with both concepts, the participants had to answer further open questions in a final survey regarding improvement of both concepts (cf. *Research Question FS 3.3*). It became clear that the display of information in the driver's primary FOV was appreciated and that the AR HUD is seen as a meaningful advancement of the conventional HUD technology. The *harpoon concept's* dominant animation was rated as supportive by the vast majority of participants. The participants stated among others that the animation showed them exactly where to turn off, did not distract them from driving, and was easy to interpret. Finally, the participants had to decide whether they liked the AR HUD or the conventional HUD better. The great majority chose the AR HUD for reasons like more accurate, more intuitive, and easier to understand. As these reasons are similar to the ones mentioned in case of the assessment of the integrated animation, the animation could have made a big impact on the participant's decision.

Some limitations have to be considered when interpreting the results of this experiment. As we wanted to focus on the evaluation of navigation concepts in HUDs, we decided to not integrate any additional audio output or map display in the vehicle's head-unit or instrument cluster. These missing hints might have irritated some participants as they are used to it when driving with a conventional HUD navigation series system. Furthermore, the participants of the study were not familiar with navigation in the AR HUD and thus, results could be different when they use this technology more frequently in the future. In literature, there is evidence that it can take up to four weeks until drivers get familiar with a new DAS like ACC (Weinberger, 2001) or a conventional HUD (Gengenbach, 1997). Accordingly, the benefits of a new driving assistance technology can be seen possibly only after this acclimatization period (Heiner Bubb, 2015a). Again, we conducted this experiment in real traffic with an actual prototype vehicle containing a complete AR HUD setup. Thus, a realistic test scenario can be achieved, but this also leads to factors that cannot be controlled, such as different light or weather conditions and differences in traffic density.

To draw a final conclusion, the findings of this field study indicate that a contact analogue navigation concept implemented in an AR HUD can be a meaningful step forward compared to the conventional HUD navigation. In the future, the technical limitations will get less, which offers even more possibilities for concept developers. The majority of the participants preferred the *harpoon concept* over the static navigation concept, among others due to the integrated animation and the accuracy of the manoeuvre point display. In terms of system trust and subjective mental workload, there were no significant differences between AR HUD and conventional HUD navigation, although, the participants drove with a contact analogue one for the first time. Participants even tended to make less navigation errors when using the AR HUD.

8 Summary and Discussion

This work addresses different aspects of concept development for AR HUD: A concept development approach for rapid prototyping based on a 3D software tool is developed and compared to a popular approach based on real-driving scenes. Also, an ideal development process for AR HUD concept design is suggested. Next, a complete navigation concept for AR HUD is developed by conducting three field studies with a prototype vehicle containing a complete AR HUD setup. Based on the findings of the field studies, design guidelines for AR HUD navigation concepts are given. This chapter includes a summary of all contributions given in this dissertation.

8.1 3D Projects for AR HUD Concept Development

In this work, two *Cinema 4D* projects are created (cf. Figure 62) to show how a 3D tool used for AR HUD concept development could look like (cf. *Research Question EE 1*). The addressed use cases are *navigation*, *lane departure prevention*, and *collision prevention assist*. In an expert evaluation this concept development approach is compared to an approach based on virtual content integrated in real driving scenes to investigate their suitability as tool for concept design. The results show that the great advantage of the 3D projects over the real-world driving scenes is the possibility to quickly and effectively compare similar concept designs in different driving scenarios (cf. *Research Question EE 2* and *EE 3*). Also, positive and negative feedback regarding both concept development approaches is collected and advice on how to extend and improve them in a meaningful way is given (cf. *Research Question EE 4*).

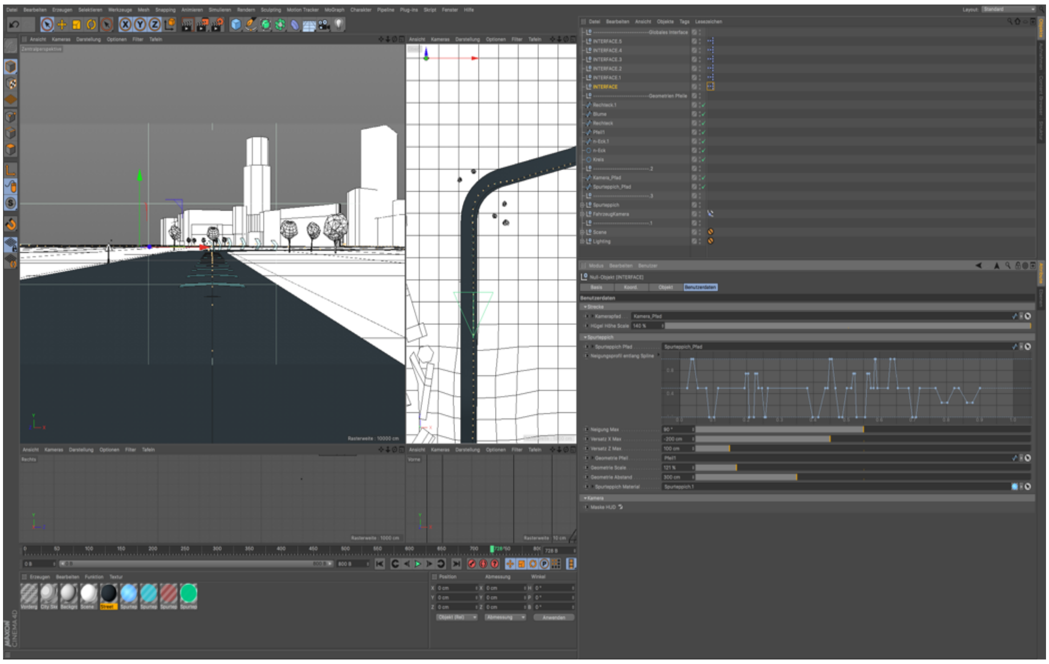


Figure 62: The concept development tool for the use case navigation based on the 3D modelling software Cinema 4D.

8.2 The AR HUD Concept Development Process

To help concept developers from the fields of research and economy with an effective development of AR HUD concepts, an ideal process together with suitable tools is suggested (cf. Figure 63) based on an expert evaluation (cf. *Research Question EE 5*). The process consists of five different phases and in every phase it's possible and sometimes necessary to go back to the previous one. In the first phase, called *brainstorming*, developers think about first concept ideas and sketch them. In the next phase, called *first concept visualisations*, some of the initial ideas will be refined and visualised. The third phase if the *advanced development phase* and represents further refinement and comparison of only a few concepts. During the fourth phase, called *concept validation*, the chosen concepts will be evaluated preferably in a realistic testing environment. In the last concept development phase, named *final submission*, all documents and files necessary will be handed over to software developers that implement the AR HUD concepts in the series system.

Of course, this concept development approach is only a suggestion and can be adapted regarding the requirements or hardware/software available in the current project or context. Thus, different alternatives are given already for the single concept development phases but can be extended with further ones.

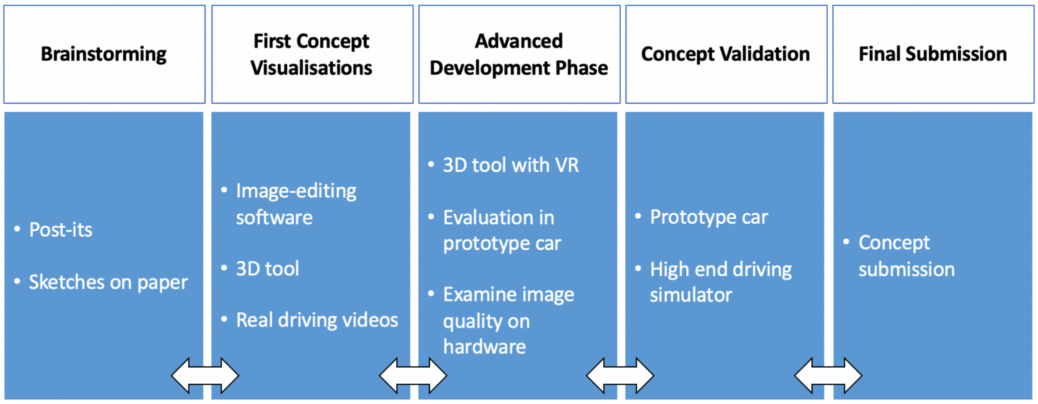


Figure 63: The suggested concept development process for an AR HUD.

8.3 The Harpoon Concept

The *harpoon concept* for AR HUD is developed based on results of concept guidelines from research and a field study conducted in the real traffic, described in Section 7.1 (cf. *Research Question CS 1*). In this experiment, two contact analogue navigation concept variants are compared with the help of a prototype car containing a full AR HUD setup. The participants are all experts in fields relevant to the development of an AR HUD. In Section 7.3, the concept is compared to a conventional HUD navigation which is already available in today's series car. The results show that the majority of participants prefer navigating with the AR HUD despite today's technical limitations. Additionally, a further improved version of the *harpoon concept* is implemented in the AR HUD of a recently released series vehicle by Mercedes-Benz, the 11th generation of the *S-class (W223)* series (cf. Figure 64). The world premiere of the vehicle will take place in fall 2020. The system contains various use cases from the areas of navigation and driving assistance (Daimler AG, 2020c).

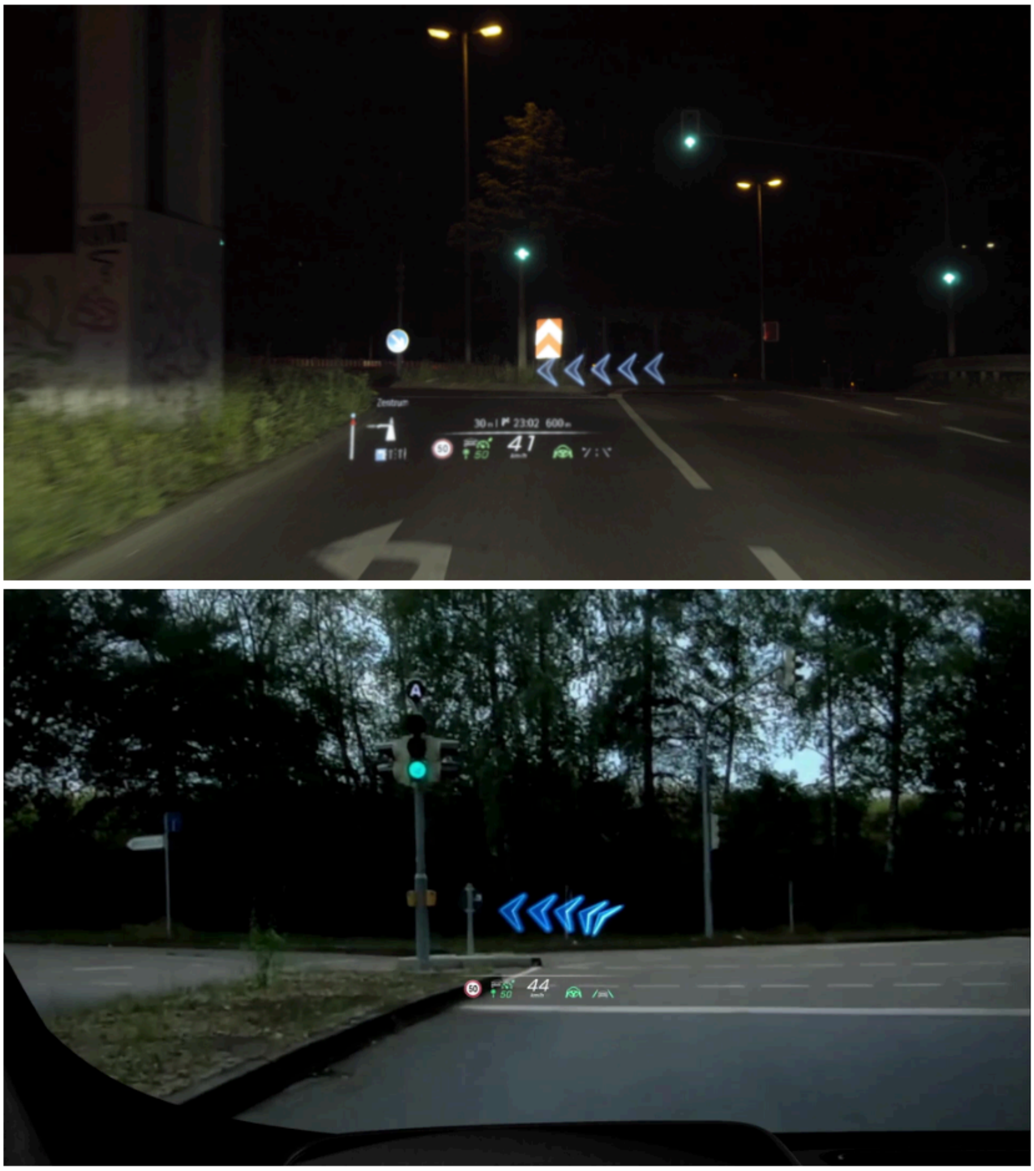


Figure 64: A revised version of the harpoon concept that got implemented in the Mercedes-Benz S-class (W223) series (Daimler AG, 2020b).

8.4 Guidelines for AR HUD Navigation Concept Development

From the findings of the field studies conducted in this work, one can derive several design guidelines for the navigation concept development for AR HUD (cf. *Research Question CS 2*). Especially, the qualitative data collected in the experiments gives valuable insights on how to design such concepts. The guidelines are valid in particular for the use case navigation but can also be helpful for the concept design of other AR HUD use cases:

Core Element: It is recommended to use fishbones as the core element of the navigation concept. At the same time, it would make sense to make brightness, colour, and number of single fishbones adaptable by the user. Further, an AR HUD navigation concept should only consist of a single core element that can morph into another one.

Pre-indication: A static pre-indication for the upcoming manoeuvre together with remaining distance should be added to a contact analogue display.

Cut-off: A cut-off of contact analogue concept elements due to the limited *field of view* should be avoided. Instead, the contact analogue content can be replaced by a static one or be clamped in the *field of view* (cf. DPMA 102019006219.1, n.d.).

Collision: A collision of contact analogue and static elements (e.g. pre-indication, speed, or traffic sign assist) should be avoided.

Masking: To avoid masking of real-world objects, concept elements can get more transparent while their outlines remain visible. Thus, masking of other objects is reduced and the navigation information is still accessible (cf. DPMA 102019007495.5, n.d.).

Contact Analogue: A contact analogue display should be used for navigation cues whenever possible as the driver gets relieved due to their intuitiveness and clearness.

Size: Concept elements should not be or get too big or dominant and cover too much of the real-world environment.

Complexity: The complexity of the displayed virtual content should be reduced when there is no upcoming manoeuvre, e.g. in case of long straight sections on motorways. However, information indicating that the navigation system is still running should remain visible.

Tilt: In case of fishbones lying flat on the street, a tilt can be added to enhance their visibility. When approaching the turn-off point, the tilt can be reduced to zero in a steady way.

Colour: Colour and brightness of the AR HUD display can be adapted regarding current weather, daytime, or light conditions.

Animation: Animation should be included to guide the driver's attention towards an upcoming manoeuvre. At the same time, the animation should be designed in a way that it clarifies the direction of the turn-off point. However, developers should make sure not to overextend the driver with an animation made too complicated or complex.

9 Future Research and Outlook

The AR HUD is a meaningful technology for motorcars that can enhance driver safety and comfort by showing driving-related information connected to the real-world environment. However, until this technology reaches commercial sale, there are still some challenges to master including fields like sensory data fusion, the optical system, and the development of best design practices.

In this work, we mainly addressed the use case navigation, as one of the most useful and complex use cases for an AR HUD. However, only basic manoeuvre cues were investigated in the presented field studies due to still existing technical limitations. In future studies, one could address more complex navigation manoeuvres (e.g. U-turns, roundabouts, and motorway access or exit) and develop suitable concepts for these. For instance, a design idea for a roundabout concept for AR HUD is presented in DE102019000901A1 (2019). Additionally, field studies should be conducted that take place in a more complex city scenario than the one used in this work (e.g. rush hour in a large city or traffic in a foreign country), to further examine the driver's mental workload and behaviour in challenging driving situations. Also, researchers have to examine, whether drivers remain attentive while navigating with an AR HUD and not follow wrong or poorly positioned contact analogue navigation cues blindly. Furthermore, it is important not to overextend the driver by showing too much information. Thus, functions should be integrated into the AR HUD that adapt the current display to support the driver in certain situations or to decrease the mental workload (see DE102017011414A1, 2017; DE102018003569A1, 2018; DE102019002541A1, 2019). Further, the displayed information can be adapted according to the outside weather (cf. DPMA 102020109970.3, n.d.) and the colour of virtual elements can be changed to the complementary colour to enhance the visibility (cf. DPMA 102020001471.2, n.d.).

Furthermore, future research should also focus on other meaningful AR HUD use cases like *lane departure prevention*, *collision prevention assist*, or *adaptive cruise control* and investigate the interplay of static and contact analogue concept elements. The aim should be to find a way to combine multiple use cases to create an overall concept for AR HUD. Even more information connected to the surrounding world can be displayed when future vehicles are able to drive fully automated, such as virtual cues that give further information concerning points of interest along the route. Furthermore, this technology could be used to increase the user's trust in autonomous driving in general (see Schömig et al., 2018; von Sawitzky, Wintersberger, Riener, & Gabbard, 2019; Wintersberger, Frison, Riener, & von Sawitzky, 2019; Wintersberger, von Sawitzky, Frison, & Riener, 2017). Also, passengers sitting next to the driver or on the rear-seat can be entertained either by using AR HUDs or head-mounted displays (see Haeling et al., 2018). Further technical advancements could be the increase of the AR HUD's *field of view* or the development of a stereoscopic HUD which offers new possibilities to display virtual content but also requires suitable design guidelines and parameters (see Broy et al., 2014). Also, AR content could be displayed in contact lenses as shown by the start-up *Mojo Vision* which created a working prototype (Perry, 2020).

When integrating the AR HUD technology in a series vehicle, developers have to examine, how drivers react to information of ADASs coming from different sources, such as instrument cluster, head-unit, HUD, ambient light, acoustic or haptic feedback, and digital light (cf. Mercedes-Benz, n.d.). Furthermore, one has to make sure to adjust the design and behaviour of the different information sources to avoid misunderstandings. That means, in addition to an overall AR HUD concept, the overall *in-vehicle experience* has to be considered.

At best, all of the suggested studies should be conducted in the field with a prototype vehicle containing a real AR HUD setup to get the most realistic results possible. The findings of these studies can be compared to findings from simulation studies to prove or disprove them. However, challenges like masking and different weather or light conditions cannot be investigated in a driving simulator and need to be addressed in future experiments in the field. To get even more realistic results, researchers should conduct future studies with real costumers rather than employees of automakers or suppliers. At the same time, different populations concerning age (see S. Kim & Dey, 2009; Pampel et al., 2019), cultural background, or gender should be addressed to provide AR HUD concepts that match best for everybody.

Finally, to get further insights on image quality, contrast, and colour, different AR HUD hardware and windshield types should be compared in a laboratory setup or the real traffic (cf. Wagner et al., 2020). These factors might have an impact on drivers as well.

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References

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Disclosures and Patent Applications

In this work, a number of inventions were created and registered. A list of the corresponding disclosures and patent applications can be find below:

Friedrich, M., Necker, M., Schirmer, F., & Schneider, M. (2017). [DE] Verfahren zur Darstellung von einer Fahrtrichtungsinformation und System zur Darstellung einer Fahrtrichtungsinformation. Patent No. DE102017011414A1. Germany.

Heinze, C., Schirmer, F., Schneider, M., & Wenz, M. (2018). [DE] Verfahren zur Darstellung eines virtuellen Inhaltes in einem Anzeigebereich einer Anzeigeeinheit eines Fahrzeuges und ein Fahrzeug. Patent No. DE102018003569A1. Germany.

Schneider, M., Preibisch, J., Schluesener, T., Hartwig, M., Friedrich, M., Huebner, M., … Mackamul, C. (2019). [DE] Verfahren zur Einblendung von Texturen in einen sich vor einem Kraftfahrzeug befindlichen Straßenverlauf, Computerprogrammprodukt sowie Kraftfahrzeug. Patent No. DE102019000901A1. Germany.

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Appendices

A. Standardized Questionnaires

A.1 Driving Activity Load Index (DALI)

DALI Fragebogen (Konventionelle Navigation)

Bitte Bewerten Sie die unten beschriebenen Kriterien in Hinblick auf Schwierigkeiten, Unsicherheiten, etc. während der Durchführung der Tätigkeit.

Faktor	Beschreibung
Allgemeine Aufmerksamkeitsbeanspruchung	Mentale (nachdenken, entscheiden,...), visuelle und auditive Beanspruchung während des Tests, für die Durchführung der Tätigkeit
Visuelle Beanspruchung	Die benötigte visuelle Beanspruchung während des Tests, für die Durchführung der Tätigkeit
Stress	Das Stresslevel während der Tätigkeit, wie Müdigkeit, Unsicherheit, Irritation, Demotivation,...
Zeitdruck	Der gefühlte Zeitdruck unter dem die Tätigkeit ausgeführt wird
Ablenkung	Ablenkung des Fahrers und Folgen für die Fahraufgabe

Jeder Faktor wird auf einer Skala von 0 (niedrig) bis 5 (hoch) hinsichtlich des jeweiligen Einschränkungslevels bewertet.

	0	1	2	3	4	5
Allgemeine Aufmerksamkeitsbeanspruchung						
Visuelle Beanspruchung						
Stress						
Zeitdruck						
Ablenkung						

A.2 User Experience Questionnaire (UEQ)

Bitte geben Sie Ihre Beurteilung ab.

Um das Produkt zu bewerten, füllen Sie bitte den nachfolgenden Fragebogen aus. Er besteht aus Gegensatzpaaren von Eigenschaften, die das Produkt haben kann. Abstufungen zwischen den Gegensätzen sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie Ihre Zustimmung zu einem Begriff äußern.

<u>Beispiel:</u>

attraktiv	○	⊗	○	○	○	○	○	unattraktiv

Mit dieser Beurteilung sagen Sie aus, dass Sie das Produkt eher attraktiv als unattraktiv einschätzen.

Entscheiden Sie möglichst spontan. Es ist wichtig, dass Sie nicht lange über die Begriffe nachdenken, damit Ihre unmittelbare Einschätzung zum Tragen kommt.

Bitte kreuzen Sie immer eine Antwort an, auch wenn Sie bei der Einschätzung zu einem Begriffspaar unsicher sind oder finden, dass es nicht so gut zum Produkt passt.

Es gibt keine „richtige“ oder „falsche“ Antwort. Ihre persönliche Meinung zählt!

Bitte geben Sie nun Ihre Einschätzung des Produkts ab. Kreuzen Sie bitte nur einen Kreis pro Zeile an.

	1	2	3	4	5	6	7		
unerfreulich	○	○	○	○	○	○	○	erfreulich	1
unverständlich	○	○	○	○	○	○	○	verständlich	2
kreativ	○	○	○	○	○	○	○	phantasielos	3
leicht zu lernen	○	○	○	○	○	○	○	schwer zu lernen	4
wertvoll	○	○	○	○	○	○	○	minderwertig	5
langweilig	○	○	○	○	○	○	○	spannend	6
uninteressant	○	○	○	○	○	○	○	interessant	7
unberechenbar	○	○	○	○	○	○	○	voraussagbar	8
schnell	○	○	○	○	○	○	○	langsam	9
originell	○	○	○	○	○	○	○	konventionell	10
behindernd	○	○	○	○	○	○	○	unterstützend	11
gut	○	○	○	○	○	○	○	schlecht	12
kompliziert	○	○	○	○	○	○	○	einfach	13
abstoßend	○	○	○	○	○	○	○	anziehend	14
herkömmlich	○	○	○	○	○	○	○	neuartig	15
unangenehm	○	○	○	○	○	○	○	angenehm	16
sicher	○	○	○	○	○	○	○	unsicher	17
aktivierend	○	○	○	○	○	○	○	einschläfernd	18
erwartungskonform	○	○	○	○	○	○	○	nicht erwartungskonform	19
ineffizient	○	○	○	○	○	○	○	effizient	20
übersichtlich	○	○	○	○	○	○	○	verwirrend	21
unpragmatisch	○	○	○	○	○	○	○	pragmatisch	22
aufgeräumt	○	○	○	○	○	○	○	überladen	23
attraktiv	○	○	○	○	○	○	○	unattraktiv	24
sympathisch	○	○	○	○	○	○	○	unsympathisch	25
konservativ	○	○	○	○	○	○	○	innovativ	26

A.3 Trust Scale

Trust Scale

Stimme überhaupt nicht zu = 1
Stimme voll zu = 7

		1	2	3	4	5	6	7
1	Das System ist irreführend.	☐	☐	☐	☐	☐	☐	☐
2	Die Aktionen des Systems sind undurchsichtig.	☐	☐	☐	☐	☐	☐	☐
3	Ich misstraue den Aktionen, Absichten oder Konsequenzen des Systems.	☐	☐	☐	☐	☐	☐	☐
4	Ich bin dem System gegenüber wachsam.	☐	☐	☐	☐	☐	☐	☐
5	Die Aktionen des Systems führen zu nachteiligen oder schädlichen Konsequenzen.	☐	☐	☐	☐	☐	☐	☐
6	Ich kann mich auf das System verlassen.	☐	☐	☐	☐	☐	☐	☐
7	Das System bietet Sicherheit.	☐	☐	☐	☐	☐	☐	☐
8	Das System ist glaubwürdig.	☐	☐	☐	☐	☐	☐	☐
9	Das System ist zuverlässig.	☐	☐	☐	☐	☐	☐	☐
10	Ich traue mir zu, das System zu nutzen.	☐	☐	☐	☐	☐	☐	☐
11	Das System ist vertrauenswürdig.	☐	☐	☐	☐	☐	☐	☐
12	Ich bin mit dem System vertraut.	☐	☐	☐	☐	☐	☐	☐

A.3 Declaration of Consent

Einverständniserklärung

Benutzerstudie von

RD/UIC Instrument Cluster & Head-up Display
Daimler AG
HPC X830
71059 Sindelfingen

Ich wurde über den Ablauf und Zweck der Studie informiert und meine Fragen wurden zufriedenstellen beantwortet.

Ich nehme freiwillig an dieser Studie teil und stimme zu, dass während der Durchführung des Interviews Aufnahmen gemacht werden (Audio und Video), die veröffentlicht werden dürfen.

Mir ist bewusst, dass meine Teilnahme an dieser Studie vertraulich ist. Alle gesammelten persönlichen Daten werden nicht ohne mein schriftliches Einverständnis an Dritte weitergegeben. Die gesammelten Informationen dienen ausschließlich Forschungszwecken.

Mir ist bewusst, dass ich die Teilnahme an dieser Studie jederzeit abbrechen kann.

____

Name, Vorname

______________________ ______________________

Ort, Datum Unterschrift

B. Questionnaires Created for the Expert Evaluation

B.1 Demographic Questionnaire

Demographische Fragen

TP - Nr. ____________

Alter: ____________ Geschlecht (m/w): ____________

Studium: ____

Beruf: ____

Erfahrung im Interface Design für Automotive: ____________________

Erfahrung in der AR HUD Konzeptentwicklung: ____________________

B.2 Persona of Interaction Designer

Persona

Name
Catherine Adams

Job
Interaction Designer

Description
Catherine is working in the concept team of a major car manufacturer working on UI concepts for the AR HUD of the next generation. In her daily work she has to talk to consult with various colleagues such as designer, developers, and manager and be open for short-term change requests.

Goals
- Create the best concepts possible for the required AR HUD use cases
- Meet the requirements of all project partners involved as well as the management

Problems
- Technical Limitations of the AR HUD system
- Requirements can change quickly
- Every person involved in the project sometimes has a different opinion or idea

B.3 Quantitative Measures for Driving Assistance (3D Tool)

3D Tool - FAS

Wie sehr stimmen Sie den folgenden Aussagen zu?

1) Dieser Ansatz eigent sich um schnell und effektiv Konzeptvarianten miteinander zu vergleichen.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

2) Dieser Ansatz unterstüzt dabei, schon früh im Entwicklungsprozess erste Management-Entscheidungen herbeizuführen.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

3) Mit diesem Ansatz können schnell und effektiv unterschiedliche Fahrsituationen untersucht werden.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

4) Dieser Ansatz bietet volle Flexibilität bei der AR HUD Konzeptentwicklung.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

5) Dieser Ansatz eignet sich zur Entwicklung eines AR HUD Konzepts.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

B.4 Qualitative Measures for Driving Assistance (3D Tool)

3D Tool - FAS (Offene Fragen)

Was gefällt Ihnen an diesem Ansatz und warum?

Was gefällt Ihnen an diesem Ansatz nicht und warum?

3D Tool - FAS (weitere Fragen)

Welche Inhalte oder Funktionen sollten hinzugefügt werden?

Welche Funktionen bzw. Inhalte werden nicht benötigt?

Um welche Inhalte könnte die Fahrszene erweitert werden?

B.5 Quantitative Measures for Driving Assistance (Real Driving Scenes)

Realfahrtszenen - FAS

Wie sehr stimmen Sie den folgenden Aussagen zu?

1) Dieser Ansatz eigent sich um schnell und effektiv Konzeptvarianten miteinander zu vergleichen.

Stimme nicht zu	☐	☐	☐	☐	☐	☐	☐	*Stimme zu*
	1	2	3	4	5	6	7	

2) Dieser Ansatz unterstüzt dabei, schon früh im Entwicklungsprozess erste Management-Entscheidungen herbeizuführen.

Stimme nicht zu	☐	☐	☐	☐	☐	☐	☐	*Stimme zu*
	1	2	3	4	5	6	7	

3) Mit diesem Ansatz können schnell und effektiv unterschiedliche Fahrsituationen untersucht werden.

Stimme nicht zu	☐	☐	☐	☐	☐	☐	☐	*Stimme zu*
	1	2	3	4	5	6	7	

4) Dieser Ansatz bietet volle Flexibilität bei der AR HUD Konzeptentwicklung.

Stimme nicht zu	☐	☐	☐	☐	☐	☐	☐	*Stimme zu*
	1	2	3	4	5	6	7	

5) Dieser Ansatz eignet sich zur Entwicklung eines AR HUD Konzepts.

Stimme nicht zu	☐	☐	☐	☐	☐	☐	☐	*Stimme zu*
	1	2	3	4	5	6	7	

B.6 Qualitative Measures for Driving Assistance (Real Driving Scenes)

Realfahrtszenen - FAS (Offene Fragen)

Was gefällt Ihnen an diesem Ansatz und warum?

Was gefällt Ihnen an diesem Ansatz nicht und warum?

B.7 Quantitative Measures for Navigation (3D Tool)

3D Tool - Navigation

Wie sehr stimmen Sie den folgenden Aussagen zu?

1) Dieser Ansatz eigent sich um schnell und effektiv Konzeptvarianten miteinander zu vergleichen.

Stimme nicht zu	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	*Stimme zu*

2) Dieser Ansatz unterstüzt dabei, schon früh im Entwicklungsprozess erste Management-Entscheidungen herbeizuführen.

Stimme nicht zu	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	*Stimme zu*

3) Mit diesem Ansatz können schnell und effektiv unterschiedliche Fahrsituationen untersucht werden.

Stimme nicht zu	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	*Stimme zu*

4) Dieser Ansatz bietet volle Flexibilität bei der AR HUD Konzeptentwicklung.

Stimme nicht zu	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	*Stimme zu*

5) Dieser Ansatz eignet sich zur Entwicklung eines AR HUD Konzepts.

Stimme nicht zu	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	*Stimme zu*

B.8 Qualitative Measures for Navigation (3D Tool)

3D Tool - Navigation (Offene Fragen)

Was gefällt Ihnen an diesem Ansatz gut und warum?

Was gefällt Ihnen an diesem Ansatz nicht und warum?

3D Tool - Navigation (weitere Fragen)

Welche Inhalte oder Funktionen sollten hinzugefügt werden?

Welche Funktionen bzw. Inhalte werden nicht benötigt?

Um welche Inhalte könnte die Fahrszene erweitert werden?

Um welche Grundkonzepte könnte man das Projekt erweitern?

B.9 Quantitative Measures for Navigation (Real Driving Scenes)

Realfahrtszenen - Navigation

Wie sehr stimmen Sie den folgenden Aussagen zu?

1) Dieser Ansatz eigent sich um schnell und effektiv Konzeptvarianten miteinander zu vergleichen.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

2) Dieser Ansatz unterstüzt dabei, schon früh im Entwicklungsprozess erste Management-Entscheidungen herbeizuführen.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

3) Mit diesem Ansatz können schnell und effektiv unterschiedliche Fahrsituationen untersucht werden.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

4) Dieser Ansatz bietet volle Flexibilität bei der AR HUD Konzeptentwicklung.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

5) Dieser Ansatz eignet sich zur Entwicklung eines AR HUD Konzepts.

Stimme nicht zu ☐☐☐☐☐☐☐ *Stimme zu*
1 2 3 4 5 6 7

B.10 Qualitative Measures for Navigation (Real Driving Scenes)

Realfahrtszenen - Navigation (Offene Fragen)

Was gefällt Ihnen an diesem Ansatz gut und warum?

Was gefällt Ihnen an diesem Ansatz nicht und warum?

B.11 Final Survey

Abschlussbefragung (Teil 1)

Welche fünf AR HUD Use Cases bieten Ihrer Meinung nach den größten Mehrwert hinsichtlich Fahrsicherheit? (ohne Reihenfolge)

Wie würde Ihr favorisierter AR HUD Konzeptentwicklungsprozess aussehen und welche Entwicklungswerkzeuge könnten hier eingesetzt werden?

Welche Parameter wären hinsichtlich Wetter und Tageszeit sinnvoll?

Welche länderspezifischen Straßensituationen wären als Erweiterung für die 3D Projekte sinnvoll?

Abschlussbefragung (Teil 2)

Bewerten Sie, wie sinnvoll folgende Entwicklungswerkzeuge im AR HUD Konzept-Entwicklungsprozess sind und in welcher Phase sie eingesetzt werden sollten.

Virtual Reality *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

AR Glasses *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

Fahrsimulator
(Moving-based mit Auto) *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

Einfacher Fahrsimulator
(Z.B. mit Gaming-Lenkrad) *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

Tischaufbau *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

Skizze auf Papier *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

Bildbearbeitungs-Tool
(Z.B. Sketch) *nicht sinnvoll* ☐ ☐ ☐ ☐ ☐ ☐ ☐ *sehr sinnvoll*
1 2 3 4 5 6 7

Einsatz: ______________________________

C. Questionnaires Created for Field Study 1

C.1 Demographic Questionnaire

Demografischer Fragebogen

Proband Nr.:
Nachname, Vorname:
Geschlecht:
Wetter:
Wie alt sind Sie?
Wie groß sind Sie? Angabe in cm
Welche Führerscheinklasse besitzen Sie?
Seit wann sind sie im Besitz Ihres Führerscheins?
Was für ein Auto fahren Sie?
Wie viel km sind sie in den letzten 12 Moanten mit dem PKW gefahren?
Haben Sie Schwierigkeiten mit dem Umgang eines Head-up Displays? (Übelkeit, Schwindel,...)
Sind Sie bereits mit einem Head-up Display gefahren?
Verfügt ihr privates Fahrzeug über ein Head-up Display?
Wie oft nutzen Sie Navigationssysteme in der Woche?
Welche Art von Navigationssystemen nutzen Sie im Fahrzeug?
Wie ist Ihre allgemeine Einstellung gegenüber Head-up Displays?

C.2 Questionnaires for Subjective Assessment

Konzept A: Fischgräte

Darstellung

1	Die Darstellung des Navigationskonzept (geometrische Form) empfand fand ich als...
	sehr unnatürlich ☐☐☐☐☐☐ sehr natürlich
	zu breit ☐☐☐☐☐☐ zu schmal
	zu klein ☐☐☐☐☐☐ zu groß
	zu dominant ☐☐☐☐☐☐ zu dezent
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm
	zu dezent ☐☐☐☐☐☐ zu aufdringlich
	zu hell ☐☐☐☐☐☐ zu dunkel
	zu deckend ☐☐☐☐☐☐ zu transparent
3	Das Navigationskonzept hat meine Erwartungen erfüllt.
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm
4	Bitte bewerten Sie das Design der AR HUD Anzeige mit einer Schulnote von 1 bis 6.
	☐☐☐☐☐☐ 1 2 3 4 5 6

Positionierung, Verdeckung, Ablenkung und Wahrnehmung

5	Die Positionierungsgenauigkeit des Navigationskonzepts in der realen Welt fand ich gut.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
6	Es hat mich gestört, dass in den Kurven die Fischgräte am Bildrand abgeschnitten wurde.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
7	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
8	Die Verdeckung der realen Welt durch die AR Inhalte hat mich gestört.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
9	Das Navigieren mit diesem Navigationskonzept für AR HUD erforderte meine volle Konzentration.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
10	Ich konnte die AR HUD-Anzeige unter den Versuchsbedingungen (Licht, Wetter, Verkehr) gut wahrnehr
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
11	Meiner Meinung nach wurde durch das Konzept zu viel von der realen Welt verdeckt.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu

Gesamtbewertung

12	INSGESAMT halte ich dieses kontaktanaloge Navigationskonzept für gelungen.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
13	Hinsichtlich der Verdeckung der realen Umgebung, bevorzuge ich Konzept:
	A ☐ B ☐

Konzept B: Fischgräte gepunktet

Darstellung

1	Die Darstellung des Navigationskonzept (geometrische Form) empfand fand ich als...
	sehr unnatürlich ☐☐☐☐☐☐ sehr natürlich zu breit ☐☐☐☐☐☐ zu schmal zu klein ☐☐☐☐☐☐ zu groß zu dominant ☐☐☐☐☐☐ zu dezent
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm zu dezent ☐☐☐☐☐☐ zu aufdringlich zu hell ☐☐☐☐☐☐ zu dunkel zu deckend ☐☐☐☐☐☐ zu transparent
3	Das Navigationskonzept hat meine Erwartungen erfüllt.
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm
4	Bitte bewerten Sie das Design der AR HUD Anzeige mit einer Schulnote von 1 bis 6.
	☐☐☐☐☐☐ 1 2 3 4 5 6

Positionierung, Verdeckung, Ablenkung und Wahrnehmung

5	Die Positionierungsgenauigkeit des Navigationskonzepts in der realen Welt fand ich gut.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
6	Es hat mich gestört, dass in den Kurven die Fischgräte am Bildrand abgeschnitten wurde.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
7	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
8	Die Verdeckung der realen Welt durch die AR Inhalte hat mich gestört.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
9	Das Navigieren mit diesem Navigationskonzept für AR HUD erforderte meine volle Konzentration.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
10	Ich konnte die AR HUD-Anzeige unter den Versuchsbedingungen (Licht, Wetter, Verkehr) gut wahrnehm
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
11	Meiner Meinung nach wurde durch das Konzept zu viel von der realen Welt verdeckt.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu

Gesamtbewertung

11	INSGESAMT halte ich dieses kontaktanaloge Navigationskonzept für gelungen.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
13	Hinsichtlich der Verdeckung der realen Umgebung, bevorzuge ich Konzept:
	A ☐ B ☐

C.3 Questionnaires with Open Questions

Offene Fragen zu Konzept A: Fischgräte

1) Was ist Ihnen an dieser AR HUD-Anzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser AR HUD-Anzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu diesem AR HUD Navigationskonzept?
4) Können Sie sich eine Kombination mit nicht kontaktanaloge Hinweise vorstellen? Wenn ja, wie könnte diese aussehen?

Zusätzliche Frage nach zweiter Fahrt:

5) Welches Navigationskonzept (Fischgräten oder gepunktete Fischgräten) fanden Sie besser und warum?

Offene Fragen zu Konzept B: Fischgräte gepunktet

1) Was ist Ihnen an dieser AR HUD-Anzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser AR HUD-Anzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu diesem AR HUD Navigationskonzept?
4) Können Sie sich eine Kombination mit nicht kontaktanaloge Hinweise vorstellen? Wenn ja, wie könnte diese aussehen?

Zusätzliche Frage nach zweiter Fahrt:

5) Welches Navigationskonzept (Fischgräten oder gepunktete Fischgräten) fanden Sie besser und warum?

D. Questionnaires Created for Field Study 2

D.1 Demographic Questionnaire

Demografischer Fragebogen

Proband Nr.:
Geschlecht:
Wetter:
Wie alt sind Sie?
Wie groß sind Sie? (Angabe in cm)
Welche Führerscheinklasse besitzen Sie?
Seit wann sind sie im Besitz Ihres Führerscheins?
Was für ein Auto fahren Sie?
Wie viel km sind sie in den letzten 12 Monaten mit dem PKW gefahren?
Haben Sie Schwierigkeiten mit dem Umgang eines Head-up Displays? (Übelkeit, Schwindel,...)
Sind Sie bereits mit einem Head-up Display gefahren?
Verfügt ihr privates Fahrzeug über ein Head-up Display?
Wie oft nutzen Sie Navigationssysteme in der Woche?
Welche Art von Navigationssystemen nutzen Sie im Fahrzeug?
Wie ist Ihre allgemeine Einstellung gegenüber Head-up Displays?

D.2 Questionnaires for Subjective Assessment

Konzept A: Fischgräte

Darstellung

1	Die Darstellung des Navigationskonzept (geometrische Form) empfand fand ich als...
	sehr unnatürlich ☐☐☐☐☐☐ sehr natürlich
	zu breit ☐☐☐☐☐☐ zu schmal
	zu klein ☐☐☐☐☐☐ zu groß
	zu dominant ☐☐☐☐☐☐ zu dezent
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm
	zu dezent ☐☐☐☐☐☐ zu aufdringlich
	zu hell ☐☐☐☐☐☐ zu dunkel
	zu deckend ☐☐☐☐☐☐ zu transparent
3	Das Navigationskonzept hat meine Erwartungen erfüllt.
	sehr angenehm ☐☐☐☐☐☐ sehr unangenehm
4	Bitte bewerten Sie das Design der AR HUD Anzeige mit einer Schulnote von 1 bis 6.
	☐☐☐☐☐☐ 1 2 3 4 5 6

Positionierung, Verdeckung, Ablenkung, Wahrnehmung und Animation

5	Die Positionierungsgenauigkeit des Navigationskonzepts in der realen Welt fand ich gut.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
6	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
7	Die Verdeckung der realen Welt durch die AR Inhalte hat mich gestört.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
8	Das Navigieren mit diesem Navigationskonzept für AR HUD erforderte meine volle Konzentration.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
9	Ich konnte die AR HUD-Anzeige unter den Versuchsbedingungen (Licht, Wetter) gut wahrnehmen.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
10	Meiner Meinung nach wurde durch das Konzept zu viel von der realen Welt verdeckt.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
11	Die integrierte Animation war meiner Meinung nach...
	störend ☐☐☐☐☐☐ unterstützend
	zu ausgeprägt ☐☐☐☐☐☐ zu dezent
	angenehm ☐☐☐☐☐☐ unangenehm
	schlecht gestaltet ☐☐☐☐☐☐ gut gestaltet

Gesamtbewertung

12	INSGESAMT halte ich dieses kontaktanaloge Navigationskonzept für gelungen.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
13	Hinsichtlich der Verdeckung der realen Umgebung, bevorzuge ich Konzept:
	Fischgräte ☐ Harpune ☐ **(nach 2. Fahrt)**

Konzept B: Harpune

Darstellung

1	Die Darstellung des Navigationskonzept (geometrische Form) empfand fand ich als...
	sehr unnatürlich ☐☐☐☐☐☐ sehr natürlich
	zu breit ☐☐☐☐☐☐ zu schmal
	zu klein ☐☐☐☐☐☐ zu groß
	zu dominant ☐☐☐☐☐☐ zu dezent
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...
	sehr unangenehm ☐☐☐☐☐☐ sehr angenehm
	zu dezent ☐☐☐☐☐☐ zu aufdringlich
	zu hell ☐☐☐☐☐☐ zu dunkel
	zu deckend ☐☐☐☐☐☐ zu transparent
3	Das Navigationskonzept hat meine Erwartungen erfüllt.
	sehr angenehm ☐☐☐☐☐☐ sehr unangenehm
4	Bitte bewerten Sie das Design der AR HUD Anzeige mit einer Schulnote von 1 bis 6.
	☐☐☐☐☐☐ 1 2 3 4 5 6

Positionierung, Verdeckung, Ablenkung, Wahrnehmung und Animation

5	Die Positionierungsgenauigkeit des Navigationskonzepts in der realen Welt fand ich gut.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
6	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
7	Die Verdeckung der realen Welt durch die AR Inhalte hat mich gestört.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
8	Das Navigieren mit diesem Navigationskonzept für AR HUD erforderte meine volle Konzentration.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
9	Ich konnte die AR HUD-Anzeige unter den Versuchsbedingungen (Licht, Wetter) gut wahrnehmen.
	trifft nicht zu ☐☐☐☐☐☐ trifft zu
10	Meiner Meinung nach wurde durch das Konzept zu viel von der realen Welt verdeckt.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
11	Die integrierte Animation war meiner Meinung nach...
	störend ☐☐☐☐☐☐ unterstützend
	zu ausgeprägt ☐☐☐☐☐☐ zu dezent
	angenehm ☐☐☐☐☐☐ unangenehm
	schlecht gestaltet ☐☐☐☐☐☐ gut gestaltet

Gesamtbewertung

12	INSGESAMT halte ich dieses kontaktanaloge Navigationskonzept für gelungen.
	trifft zu ☐☐☐☐☐☐ trifft nicht zu
13	Hinsichtlich der Verdeckung der realen Umgebung, bevorzuge ich Konzept:
	Fischgräte ☐ Harpune ☐ **(nach 2. Fahrt)**

D.3 Questionnaires with Open Questions

Offene Fragen zu Konzept A: Fischgräte

1) Was ist Ihnen an dieser AR HUD-Anzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser AR HUD-Anzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu diesem AR HUD Navigationskonzept?

Zusätzliche Frage nach zweiter Fahrt:

4) Hat sie die ausgeprägtere Animation bei Konzept Harpune beim Navigieren eher unterstützt oder gehindert und warum?
5) Welches Navigationskonzept (Fischgräten oder Harpune) fanden Sie besser und warum?

Offene Fragen zu Konzept B: Harpune

1) Was ist Ihnen an dieser AR HUD-Anzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser AR HUD-Anzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu diesem AR HUD Navigationskonzept?

Zusätzliche Frage nach zweiter Fahrt:

4) Hat sie die ausgeprägtere Animation bei Konzept Harpune beim Navigieren eher unterstützt oder gehindert und warum?
5) Welches Navigationskonzept (Fischgräten oder Harpune) fanden Sie besser und warum?

E. Questionnaires Created for Field Study 3

E.1 Demographic Questionnaire

Demografischer Fragebogen

Proband Nr.:
Geschlecht:
Wetter:
Wie alt sind Sie?
Wie groß sind Sie? (Angabe in cm)
Welche Führerscheinklasse besitzen Sie?
Seit wann sind sie im Besitz Ihres Führerscheins?
Was für ein Auto fahren Sie?
Wie viel km sind sie in den letzten 12 Monaten mit dem PKW gefahren?
Haben Sie Schwierigkeiten mit dem Umgang eines Head-up Displays? (Übelkeit, Schwindel,...)
Sind Sie bereits mit einem Head-up Display gefahren?
Verfügt ihr privates Fahrzeug über ein Head-up Display?
Wie oft nutzen Sie Navigationssysteme in der Woche?
Welche Art von Navigationssystemen nutzen Sie im Fahrzeug?
Wie ist Ihre allgemeine Einstellung gegenüber Head-up Displays?

E.2 Questionnaires for Subjective Assessment

Konzept: AR HUD Navigation

Allgemeine Fragen

1	Das Design des Navigationskonzept empfand ich als ansprechend			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...			
	sehr angenehm	☐☐☐☐☐☐☐	sehr unangenehm	
3	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
4	Das Navigieren mit diesem Navigationskonzept erforderte meine volle Konzentration.			
	trifft zu	☐☐☐☐☐☐☐	trifft nicht zu	
5	Ich konnte die AR HUD-Anzeige unter den Versuchsbedingungen (Licht, Wetter) gut wahrnehmen.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	

Sonderfragen AR HUD

6	Die Verdeckung der realen Welt durch die AR Inhalte hat mich gestört.			
	trifft zu	☐☐☐☐☐☐☐	trifft nicht zu	
7	Meiner Meinung nach wurde durch das Konzept zu viel von der realen Welt verdeckt.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
8	Das AR HUD Navigationskonzept hat mich von der eigentlichen Fahraufgabe abgelenkt.			
	trifft zu	☐☐☐☐☐☐☐	trifft nicht zu	
9	Das verbaute AR HUD hat meine Erwartungen erfüllt.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
10	Es hat mich gestört, dass die Positionierung stellenweise ungenau war.			
	trifft zu	☐☐☐☐☐☐☐	trifft nicht zu	
11	Das Navigieren mit dem AR HUD gab mir ein Gefühl von Sicherheit.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
12	Insgesamt fand ich das Navigieren mit dem AR HUD als...			
	sehr angenehm	☐☐☐☐☐☐☐	sehr unangenehm	

Gesamtbewertung

13	INSGESAMT halte ich dieses Navigationskonzept für gelungen.			
	trifft nicht zu	☐☐☐☐☐☐☐	trifft zu	
14	Bitte bewerten Sie das Navigationskonzept mit einer deutschen Schulnote von 1 bis 6.			
		☐☐☐☐☐☐ 1 2 3 4 5 6		

Konzept: Konventionelle Navigation

Allgemeine Fragen

1	Das Design des Navigationskonzept empfand ich als ansprechend
	trifft nicht zu ☐☐☐☐☐☐☐ trifft zu
2	Die farbliche Gestaltung der Navigationspfeile empfand ich als...
	sehr angenehm ☐☐☐☐☐☐☐ sehr unangenehm
3	Es fiel mir leicht, die dargestellten Navigationshinweise zu erkennen und zu interpretieren.
	trifft nicht zu ☐☐☐☐☐☐☐ trifft zu
4	Das Navigieren mit diesem Navigationskonzept erforderte meine volle Konzentration.
	trifft zu ☐☐☐☐☐☐☐ trifft nicht zu
5	Ich konnte die Navi-Anzeige unter den Versuchsbedingungen (Licht, Wetter) gut wahrnehmen.
	trifft nicht zu ☐☐☐☐☐☐☐ trifft zu

Gesamtbewertung

13	INSGESAMT halte ich dieses Navigationskonzept für gelungen.
	trifft nicht zu ☐☐☐☐☐☐☐ trifft zu
14	Bitte bewerten Sie das Navigationskonzept mit einer deutschen Schulnote von 1 bis 6.
	☐☐☐☐☐☐ 1 2 3 4 5 6

E.3 Questionnaires with Open Questions

Offene Fragen zu Konzept: AR HUD Navigation

1) Was ist Ihnen an dieser Navigationsanzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser Navigationsanzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu dieser Navigationsanzeige?

Offene Fragen zu Konzept: Konventionelle Navigation

1) Was ist Ihnen an dieser Navigationsanzeige besonders positiv aufgefallen?
2) Was ist Ihnen an dieser Navigationsanzeige besonders negativ aufgefallen?
3) Haben Sie Verbesserungsvorschläge/weitere Bemerkungen zu dieser Navigationsanzeige?

Content of the Digital Appendix

/1_Dissertation	Written dissertation as PDF and DOCX file
/2_Figures	Figures created for this work
/3_Standardised Questionnaires	Standardised questionnaires used in multiple studies
/4_Expert Evaluation	Questionnaires, Cinema4D files, raw data, and evaluation of the Expert Evaluation
/5_Field Study 1	Questionnaires, 3D objects, raw data, and data analysis of Field Study 1
/6_Field Study 2	Questionnaires, raw data, and data analysis of Field Study 2
/7_Field Study 3	Questionnaires, raw data, and data analysis of Field Study 3