EXTENDING HEAD-UP DISPLAYS

EXPLORING THE POTENTIAL OF LARGE & 3D AUTOMOTIVE WINDSHIELD DISPLAYS

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RENATE HÄUSLSCHMID

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Erstgutachter:	Prof. Dr. Andreas Butz
Zweitgutachter:	Prof. Dr. Andrew Kun
Drittgutachter:	Prof. Dr. Martin Baumann
Berichterstatter:	Prof. Dr. Peer Kröger
Zweitbetreuer:	Prof. Dr. Tobias Höllerer

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Renate Häuslschmid

ABSTRACT

Drivers consume an increasing amount of information while driving. The information is accessed on the in-car displays but also on personal devices such as the smartphone. Head-up displays are designed for a safe uptake of additional visual information while driving but their benefits are limited by the small display space. This motivates academia and industry to advance the head-up to the so-called *windshield display*. A windshield display will provide an extended display space, which largely or entirely covers the driver's visual field through the windshield, as well as 3D and depth perception. Technologically, they are not yet feasible, but, thanks to steady advancements they will become available in the future. Extending a small 2D to a large 3D space requires a rethinking of the entire user interface. The windshield display opens up new opportunities for the type and amount of information, as well as for the way it is presented – ranging up to full *augmented reality* but it also raises concerns about a distracted driver.

The core question of this thesis is whether such an extension is reasonable and desirable – meaning if there are convincing arguments and use cases which justify the potential risk of distraction. This thesis presents our research about the risks and benefits of the transition from a head-up to a windshield display. Thus, we explore the potentials and examine the safety risks and benefits as well as the drivers' satisfaction of various display aspects.

We developed a design space that shows how the new size and depth possibilities create new, or interrelate with existing, design factors. New design opportunities arise and suggest a redesign of existing functionality but also the integration of new content. We researched the information content that could be displayed on a windshield display and asked drivers what content they need and personally desire. We thereby obtained an extensive list of use cases and applications. We approached the question of where such content should be displayed, given the large 3D space.

To enable the design of safe interfaces, we first examined the driver's visual perception across the windshield and identified locations that promote information recognition, particularly in the new peripheral area. Simultaneously, we examined the different ways of placing and stabilizing the content. We compared the traditional screen-fixed with world-fixed (augmented reality) and head-stabilized placement methods in terms of user satisfaction, understandability and safety. The gained knowledge about the locations that support information uptake and about the best ways of placing content was merged into a layout concept that subdivides the driver's view into several information areas. We also incorporated the drivers' preferences into this design process and compared their personalized layouts with our vision-based layout concept. We assessed the safety of both layout versions and present a revised concept.

We close this thesis by reflecting on other trends that may interrelate with the windshield display, namely autonomous driving and augmented reality consumer devices. We look at recent advancements in realizing windshield displays and endeavor a prediction of future developments in this area.

ZUSAMMENFASSUNG

Autofahrer konsumieren zunehmend mehr Informationen während der Fahrt. Diese Informationen werden über die fahrzeugeigenen Displays oder persönliche Geräte wie zum Beispiel Smartphones bezogen. Das Head-Up Display ist für die Aufnahme zusätzlicher, visueller Informationen während der Fahrt optimiert. Die Vorteile dieses Displays können jedoch aufgrund der limitierten Anzeigefläche nur begrenzt ausgeschöpft werden. Die Automobilindustrie und Forschungsinstitutionen arbeiten daher an der Entwicklung des sogenannten *Windshield Displays*. Das Windshield Display wird eine großflächige oder gesamte Abdeckung des Blickfelds durch die Windschutzscheibe und potentiell auch 3D und damit Tiefeneindrücke ermöglichen. Neuere Head-Up Versionen nähern sich dem Ziel in kleinen Schritten und lassen eine Realisierung des Windshield Displays erhoffen. Die Erweiterung von der kleinen zweidimensionalen Anzeigefläche zu einem großen dreidimensionalen Raum verlangt ein Überdenken des gesamten Anzeige- und Interaktionskonzepts. Das Windshield Display ermöglicht die Anzeige von neuen und mehr Informationen sowie neue Darstellungsarten die einer Erweiterung der Realität (*Augmented Reality*) nahekommen. Mit dieser Entwicklung erhöht sich jedoch auch das Risiko der Fahrerablenkung.

Diese Dissertation zentralisiert die grundlegende Frage ob die Erweiterung vom Head-Up zum Windshield Display hinsichtlich des Ablenkungsrisikos sinnvoll ist und präsentiert unsere Forschung über die damit einhergehenden Risiken und Chancen. Wir explorieren das Potenzial eines solchen Displays durch die Untersuchung des Einflusses verschiedener Displayfaktoren auf die Sicherheit sowie die Nutzerzufriedenheit.

Wir haben den Design Space abgesteckt und zeigen anhand dessen wie Displaygröße und -tiefe neue Designfaktoren erschaffen und mit bestehenden in Beziehung stehen. Die neuen Darstellungsmöglichkeiten legen ein Redesign der existierenden Funktionalität aber auch die Integration von neuen Inhalten nahe. Wir haben potentielle Inhalte für ein Windshield Display untersucht und Autofahrer nach ihren Bedürfnissen und persönlichen Präferenzen befragt. Dies resultierte in einer umfangreichen Liste von Use Cases und Anwendungen. Zudem haben wir uns mit der Platzierung dieser Inhalte innerhalb des möglichen Anzeigebereichs innerhalb der Windschutzscheibe befasst.

Um das Design sicherer Interfaces zu ermöglichen haben wir zuerst die visuelle Wahrnehmung des Fahrers innerhalb dieses Sichtbereichs untersucht. Dafür haben wir Positionen identifiziert welche die Informationsaufnahme begünstigen, insbesondere im peripheren Sichtbereich, und parallel die verschiedenen Arten der Informationsplatzierung und -stabilisierung untersucht. Wir verglichen die klassische Display-fixierte Anzeige mit der Welt-stabilisierten Platzierung (Augmented Reality) und der Kopf-stabilisierten Platzierung in Bezug auf Nutzerzufriedenheit, Verständlichkeit und Sicherheit. Das hierbei gewonnene Wissen über die vorteilhaftesten Positionen und Platzierungsstrategien wurde in einem Layoutkonzept zusammengeführt, welches den Sichtbereich des Fahrers in Informationsbereiche unterteilt. Die Wünsche und Bedürfnisse der Autofahrer hinsichtlich des Inhalts sowie dessen Platzierung wurden in diesen Designprozess einbezogen. Wir haben die Verteilung sowie die Sicherheit der persönlichen Layouts von Autofahrern mit unserem wahrnehmungsbasierten Layout verglichen und dieses daraufhin optimiert.

Abschließend diskutieren wir aktuelle Trends – insbesondere autonomes Fahren und Augmented Reality Konsumentenprodukte – und deren Bedeutung für das Windshield Display. Zudem reflektieren wir aktuelle Entwicklungsfortschritte und prognostizieren wie das zukünftige Windshield Display aussehen könnte.

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RESEARCH SYNOPSIS

1
INTRODUCTION

The task of *driving a car* requires the driver to continuously perceive the scene, understand the situation, decide which (re-)action is needed and to execute it [42]. Accordingly, supporting the drivers in one of these sub-tasks can increase their overall performance, which directly influences safety. Hence, car manufacturers have been developing systems that provide assistance or feedback for already more than 100 years (e.g., speedometer). These systems were proven helpful and increased road safety, however, they potentially bring along driver distraction. To optimize information uptake and to counter distraction, the classic dashboard display (head-down-display, HDD) was complemented with an additional readout placed close to the driver's center of attention. The so-called head-up display (HUDs) is reflected into the windshield and creates a semi-transparent image, which floats above the tip of the car's hood (see figure 1.1).

Head-up displays were introduced to the automotive domain in 1988 by General Motors [126]. Within the past 30 years, HUDs have evolved tremendously and are still subject of research and development. Technological advancements along with the advertised safety benefit promoted their popularity and sale. Developments in the consumer area are now pushing car manufacturers to keep up with recent trends: Particularly young users are permanently online and socially connected through their smartphones [71]. Augmented and virtual reality have only been commercially available for a short time but their integration into the car is already largely discussed [62]. Overall, people face and consume a growing amount of information. The same motivation causes people to use in-car and brought-in devices, such as smartphones, while driving. Reading on and interacting with small displays far away from the road scene can cause high levels of distraction from the driving task resulting in fatal accidents. Many countries passed laws against phone use while driving. However, these seem to be ineffective: Eight out of ten drivers between 16 and 20 years admit to break those laws [16]. 80% of all fatal accidents can be traced back to phone use, which underlines the need for new approaches [51]. One approach is to provide new, carefully examined, display space and interface concepts, which replace the less safe equivalents.

Researchers argue that *'the use of a HUD to display phone-related information is of particular importance'* [120]. HUDs are safer than other in-car displays but limited in space (see section on *Risks & Benefits*). A HUD with an extended screen size and possibly multiple display layers at separate depths or even a continuous depth coverage (3D) – referred to as windshield display (WSD) – may provide the required display space (see figure 1.1). Content that is now provided on head-down displays, such as most info- and entertainment functions, but also the interface of smartphone applications could be rearranged and accessed on the WSD. A new design space emerges and opportunities for new content, interface and interaction approaches arise, such as augmented reality (AR).

Designers need to balance the opportunities against the risks of the new WSD interfaces and to consider the driver (e.g., abilities), the tasks (e.g., priority of driving) and the context (e.g., driving situation). This corresponds to a highly dynamic formation that is sensitive to influences from the outside, such as distractions caused by the WSD interface. Increased load and distraction induced by additional information are directly associated with a risk of safety and have to be kept to a minimum. Supportive information needs to be distinguished from superfluous content which emphasizes the need for a human-centered approach. This requires a true understanding of the drivers' desires and needs but also of their cognitive and sensory abilities and limitations in relation to the tasks at hand.

The driver's focus point is primarily targeted to the forward scene but wanders – partially consciously controlled – within the field of view [123]. Salient peripheral stimuli, no matter if real or artificial, have the power to draw attention – also unwillingly (see section on *Information Perception*). A windshield display will provide an extensive three-dimensional information space that merges with the road scene – both can be perceived and processed in small chunks within short subsequences but not simultaneously as they compete for the same, primarily visual, resources [80]. The road scene outranks the WSD content – yet, the comprehensive perceptibility of both is essential for safety and has to be guaranteed through appropriate interface design. Such an interface would require little cognitive and visual resources. As the human vision is neither constant nor consistent throughout the visual field it limits the ability to detect and recognize potentially safety-relevant information. Information uptake has to be promoted through appropriate design of the individual items (e.g., their size and appearance) as well as their layout. By choosing locations that reflect the relevance of the item's content, perceptibility should be balanced against distraction. The time and effort needed for context switches may further be lowered through spatial proximity and contentual relation – the key characteristics of augmented reality – however, its impact on the driver is not yet fully understood [41].

This thesis is concerned with the transition from a conventional head-up to a more futuristic windshield display. We define a new design space and recognize the extension of the display size and depth coverage as the key transitions. The newly spanned three-dimensional display space will accommodate diversified content and require new information placement approaches. Both are central research topics of this thesis. The thesis closes with forecasting what a future windshield display could look like.

Figure 1.1: The left image shows an exemplary head-up display of conventional size. It indicates the limited display space and content capacity. The right image visualizes a futuristic 3D windshield display. This mockup uses the entire windshield as display space and presents additional content to the driver.

2
RESEARCH OVERVIEW

This chapter gives a quick overview of the research described in this thesis. It explains how we look at windshield display research and approach it without knowing about the eventual construction and abilities of such a display. Furthermore, it narrates the story behind this thesis and explains how we came up with the questions that guided our research (*RQs*). Lastly, we summarize the main contributions of this thesis.

2.1 Research Perspective & Methods

The human aspects of human-computer-interaction (HCI) are based on psychological foundations. Yet, those foundations are theories with varying fidelity and validity. By iteratively controlling the input and measuring the output, researchers try to understand the *human* and find evidence that speaks in favor of or against those theories. This thesis is situated in the cross-field of automotive user interfaces which typically regards the human driver as a *user* and specifies the driving context. In manual driving, the car's interior is framed as the driver's workplace but increasingly regarded as a personal space that also needs to support tasks that go beyond manoeuvring the car. Additional systems are integrated into the car with the aim to simplify the drivers' *primary* duty of controlling the car or to satisfy personal needs. Such systems and the corresponding *secondary* driving-related and *tertiary* non-driving-related tasks [18] influence the drivers' performance and satisfaction. When dividing visual and cognitive resources to two or more tasks, one will experience a loss in the performance of each task (depending on the task difficulty [133]). The quantification of this loss is crucial as distraction and overload may lead to driving errors and delays in recognizing hazards, which put lives at risk.

Researchers try to evaluate such additional in-car systems and tasks with a combination of methods, such as user studies in a realistic simulation (applied research) [41]. Early-stage research is conducted exclusively in the laboratory to minimize the safety risks before road use is admissible. Real world studies have to be pursued in a later step. As part of this thesis, we conducted applied, human-centred research in laboratory settings only.

Research in the Absence of a Real Windshield Display The drivers' performance is relevant for the safety and the satisfaction strongly influences the acceptance of such a system. Accordingly, safety and acceptance are two major aspects researched in the field of automotive user interfaces. For both aspects, the validity of the results depends on the realism of the evaluated system and the test environment. Gish and Staplin [42] emphasize the importance of a HUD prototype that is as close to a real HUD as possible. However, the technological realization of the HUD does not scale to the entire windshield. At the time of the presented research, the eventual technological construction of the windshield display is unknown and still a challenge. Consequently, we cannot develop a prototype that is comparable to a WSD. Instead, we developed various prototypes that support the goal of this thesis – the exploration of the extension from HUD to WSD. We utilized a prototype that is constructed similarly to a conventional HUD whenever a large single-layered display space was sufficient for the study. The results of those studies are meaningful and valid for the conventional HUDs (with the general limitations of driving simulator studies). However, to research depth or full-size windshield displays we needed to utilize 3D display technology.

When exploring the change from HUD to WSD, we need to look into both performance and satisfaction. However, we are aware that our results and particularly the performance measurements are of limited generalizability and that their relevance depends on the future WSD. While the major finding will presumably remain true, the extent of the alteration in performance or satisfaction will vary in (long-term) real world use. This problem exists for all novel concepts and preliminary systems and simply points at the need for iterative research cycles which are coordinated with the display development stage. In other words, we now explore various concepts to identify the ones that are valuable to be revisited in highly realistic safety studies once a WSD is available.

Study Design In driving simulator studies, a controlled simplification of driving serves as a baseline or control group. The intervention or test group is furthermore requested to explore an additional system or execute a specific task. This enables the assessing of the system's impacts on the *human* by quantifying the performance variations. This procedure is repeated for each of the test conditions and completed by all (within-subject) or a subset of the participants (between-subject) in a controlled, mostly counter-balanced order. We primarily applied within-subject designs as those allow a direct comparison of all conditions and provide, due to the common baseline, more meaningful results. We applied between-subject designs in two studies as a compromise between the number of testable conditions (WSD locations) and study duration.

Methods & Metrics In addition to a realistic HUD prototype, Gish and Staplin [42] recommend to create a realistic test environment, allow drivers to familiarize themselves with this environment and practice the tasks as well as to impose a varying but realistic workload. All of our user studies are carried out in a driving simulator. As the driving task as well as the information uptake require almost exclusively the visual channel [28], we aimed for setups that provide a visual experience similar to real driving. We ensured that the driving scene is placed accurately; meaning that the road's vanishing point matches the drivers' straight line of sight and that the windshield's retainer limits the field of regard on the driving scene realistically. Still, the simulator software is of limited visual realism and its tasks are simplified to increase controllability and generalizability. To increase visual realism, we also used driving footage and a complementary driving task instead of a simulated scene.

We always used a dual-task scenario and emphasized the priority of the driving task. For the driving we used the standardized lane change, car-following and ConTRe task or a free-riding task (see *Terms and Abbreviations*), similar to other researchers [34, 38, 54, 59]. Drivers were always introduced to the simulation environment and the tasks. They were further requested to practice the driving task before the actual study started. The secondary tasks were only practiced when we could preclude the risk of a study bias. As secondary task, we chose the detection-response task or a monitoring task, as also applied by other HUD researchers (e.g., [119, 137]). The detection-response task is highly controllable and provides solid metrics but regards exclusively the uptake of occurring information. The monitoring task is less controllable but allows for a more realistic and self-controlled information uptake strategy. The selection of the secondary task was based on the study's goals. We designed our tasks to impose rather high workloads in order to expose even small differences between the systems or test conditions. In situations with lower workload this difference may be less pronounced.

In terms of the metrics and measurements, Gish and Staplin [42] recommend to log the driving performance, measure the response times to all tasks and to track the drivers' eyes. The driver's performance is primarily evaluated through objective and quantitative measurements such as telemetric data and response times but can be backed up with the drivers' (subjective) self reports, e.g., by means of a workload questionnaire. Questionnaires are also used to collect qualitative data that provides insights into the drivers' subjective opinion, satisfaction and acceptance of the experienced system or situation. We measured the drivers' performance through standard metrics such as the response time to events or the lateral deviation. When researching visual perception, we also often tracked the drivers' eyes. Qualitative data was collected through questionnaires which aimed at receiving the drivers' personal feedback and, if possible, to directly contrast the tested systems.

2.2 Research Approach & Questions

Industry and academia invest a lot of effort into extending the HUD's display size and depth range. Reflecting on the risks of in-car displays, we were concerned the danger may grow with the display's abilities. Repeatedly, we left discussions with one fundamental but open question:

Lead RQ: *Is the extension of the head-up to the windshield display reasonable and desirable?*

In other words, are there convincing arguments and use cases which justify the potential risk of distraction? As for the small-sized HUD, research showed that its benefits can outweigh the risks (see section on *Safety Risks & Benefits*), provided its interface is responsibly designed and used. Yet, considering the new display space and depth coverage, we wondered if there is content that (A) is worth of being presented to the drivers, (B) requires or profits from the extended display space and (C) potentially benefits from a separation in depth, or registration with the physical world. The first research step seemed obvious to us:

RQ 1: *Which content could be presented on the windshield display?*

In a first step, we analyzed HUD and WSD publications and patents for already existing applications and ideas. We further gathered insights into the drivers' interests by means of focus groups, brainstormings and an online survey. The online survey targeted content that is well-known from in-car displays and personal devices and its transfer to the WSD. The focus groups and brainstormings delivered numerous distinct use cases and application ideas and showed clearly how the participants' description of the content was tied to its design. The provision of new display space and (potentially) depth requires a rethinking of the conventional HUD interface and led to the question

RQ 2: *What design opportunities do HUDs and WSDs provide?*

Based on the extracted design approaches, ideas and principles, we developed a design space for HUDs and WSDs as a support for researchers and practitioners. With the application ideas and the design space at hand the drive for exploration grew. Driving is a safety- and time-critical task and so potentially distractive in-car applications have to be investigated in lab studies before the use on real roads can be considered. However, the technological realization of windshield displays is still subject of research itself. The need for self-developed prototypes was apparent and so we created a variety of WSD prototypes to meet the needs of our studies. These setups target mainly the two key characteristics of WSDs; the *display size* and *depth coverage*. The WSD spans a large 3D space and provides new opportunities for the content and its design but also its placement. Content needs to be placed carefully to minimize driver distraction. For a safe placement we need to understand the driver's visual perception and particularly the recognition of information within this 3D space. As the perceptual abilities are not constant throughout the visual field, we asked ourselves

RQ 3: *Which windshield display locations support information uptake?*

We targeted this question in three lab studies. Two consecutive lab studies investigated the drivers' performance in responding to basic WSD stimuli and resulted in a model for legible stimuli sizes on a 2D WSD. The third study utilized a full-size 3D windshield display and additionally regarded the depth placement. Knowing about the drivers' perception and performance in information uptake, we can move one step further and identify the locations which enable high performance *and* do not interfere with the perception of the driving scene. We thereby approached the question

RQ 4: *At which windshield display locations should content be placed?*

For most of the previously identified content, such as a speedometer or a personal message, there is no natural location within a 3D space. Yet, its presentation on the windshield may be required due to personal preferences or safety benefits. The complexity of the problem drove us to approach this issue with an iterative and human-centered design process from two sides: We developed a layout concept (*view management*) that suggests windshield areas for the display of specific content. It connects our prior research about the drivers' perception with their content preferences. In two augmented virtuality studies and an online survey we concurrently asked drivers where they would like to see exemplary content and thereby gathered personalized layouts. Subsequently, we extracted patterns from the personalized layouts and derived recommendations for the placement on future WSDs. A revised version of the concept is provided in the *Appendix [B]* of this thesis.

Yet, there is a natural location for some information. Augmented reality suggests to provide digital information spatially close to the related real world object – which supports fast and easy understanding. Augmented reality is a key motivation for the extension of the HUD to the WSD. However, correct depth placement on conventional HUDs is not yet feasible and so the effects on the driver are not yet investigated and sufficiently understood. We therefore targeted the question

RQ 5: *Which placement strategies are suitable for the windshield display?*

We approached this question in three studies that compared the three major registration types regarding response performance and perception of the surroundings. We compared 2D-registered hazard warnings with the screen-fixed equivalent on conventional HUDs. The third user study contrasted a conventional dashboard display setup with a head-stabilized HUD for motorcyclists.

The presented topics and questions as well as how we approached them is explained in more depth in the chapter *From HUD to WSD*. The order of the presented research topics and questions is adapted for better understanding. A brief summary of our findings and answers to these questions is provided in the section on *Conclusions*.

2.3 Main Research Contributions

The research conducted as part of this thesis resulted in *conceptual*, *constructive*, or *empirical* contributions (based on the HCI problem classification from Oulasvirta and Hornbaek [91]). Conceptual contributions aim at identifying and explaining phenomena without previously known interrelations. We classify our literature reviews, concepts and models as conceptual contributions. Empirical contributions aim at creating and elaborating the explanations of those phenomena. We regard the results of our applied human-centered research such as user studies, surveys, focus groups and observations as empirical contributions. Constructive contributions aim at fostering understanding about a system and particularly its fundamental ideas and principles. This thesis' software and hardware prototypes fall into the category of constructive contributions.

Considered as a whole, this thesis presents three main contributions: a design space (*conceptual*), content and applications (*conceptual & empirical*) and our research about information placement (*conceptual & empirical*). Below, we briefly introduce these contributions and refer to the corresponding sections and publications.

Design Space The design space specifies the differences between HUDs and WSDs and outlines the design options for both. It comprised the areas of user, context, visualization, interaction and technology. We based the design space on literature, already displayed and potential information content and applications for all types of in-car window displays and the options and factors identified in a focus group. The design space is described in detail in section *Design Space* and the publication [P7].

Content & Applications We collected potential content and applications for HUDs and WSDs which is imaginable and desirable for drivers. We first gathered already existing content, ideas and applications from the literature and extended this list by means of focus groups and surveys. The results are presented in section *Information Content* and the publications [P1, P7].

Information Placement We contribute a layout concept and fundamental guidelines for placing information (*view management*) on a 3D windshield display. This concept was developed iteratively and builds upon several substantial contributions: The concept is founded on our and related studies about the drivers' visual perception. We contribute response time measurements for a large field of view and a model for legible stimuli sizes (see section on *Information Perception* and the publication [P5]). We furthermore compared different strategies for placing information on the WSD, namely world-fixed, head-fixed and particularly screen-fixed placement (see section on *Information Placement Strategies* and the publications [P2, P9]). We further contribute personalized information layouts of experienced car drivers and the assessment of fundamental patterns as well as their safety. These personalized layouts are considered in the suggested layout concept. We contribute a quantitative evaluation of both the drivers' personalized layouts and the suggested concept (see section on *Information Layout* and the publications [P1, P8]).

3

CURRENT HEAD-UP DISPLAYS

HUDs present primarily driving-related content with the goal to lower the distraction and effort of information uptake and thereby increase safety. The HUD is reflected into the windshield so that it appears like a transparent display that floats above the car's hood. To the driver the image seems to merge seamlessly with the driving scene. Below, we explain how such an image is technologically realized and which information it superimposes, explain the known positive and negative impacts on the driver and show why researchers aim to extend the HUD to a large 3D windshield display.

3.1 State of the Art Head-Up Displays

Technological Realization Conventional HUDs are based on the principle of light reflection. A 2D display or projection unit is positioned at an angle of 40–45° to a transparent glass pane (*combiner*) which reflects the light and creates a virtual image visible to the observer. The observer perceives the virtual image in a distance that corresponds to the light path between eyes and combiner plus combiner and light source (source-to-eye distance) [42]. Optical elements such as mirrors and lenses can increase the light path's length and help keeping the dimensions of the entire optical setup low, which is restricted through the dashboard space. Thereby, also the size and distance of the generated image is limited [86]. Betancur and colleagues [8, 9] describe the construction of head-up displays and its challenges in more detail.

Image Dimensions The driver's field of view through the windshield measures about $67 \times 20°$ [118, 131]. The HUD's image size measures approximately $6° \times 2°$ [6, 99]. It is restricted through the dashboard space and interrelates with the image distance: An extension of the image distance decreases the perceived image size and quality [42]. According to the examples of Langlois et al. [66], the image size increases linearly with the required dashboard space.

Image Location The HUD is positioned prominently, 5° below the driver's normal line of sight (when focusing straight ahead on the lead car or the vanishing point of the road). Several studies were carried out to identify the optimal HUD location based on the driver's information recognition (speed) and preferences (e.g. [120, 137]). However, researchers restricted the tested area to approximately $20° \times 10°$ around the driver's line of sight and thereby may have biased the findings. For example, many drivers place their navigation devices above the center stack and researchers found this location to foster high monitoring performance [65], but this location was initially excluded.

Image Distance The image floats in a distance of approximately 2–2.5 m, from the driver's eyes [6, 99]. This alleviates the eye accommodation when switching focus between display and world. Several studies have been devoted to the optimal viewing distance and concluded a distance between 2–3 m, which corresponds to the eyes' resting distance [41]. Inuzuka et al. [53] tested a range of 1–5 m and showed that recognition times of older drivers increase when the stimuli is closer than 2.5 m. Like for the location, these studies often limited the range to few meters and participants did not have the opportunity to experience larger distances. Also car manufacturers and suppliers think that a larger distance is desirable, as next generation HUDs and concept cars show (see chapter on *Future Windshield Displays*).

HUD Content Head-up displays present primarily driving-related information. The content depends on the manufacturer and the car's features but may include speed, speed limit and other restrictions, vehicle status notifications such as remaining gas, headway warnings, cruise control and route guidance information [2, 6, 10]. Nowadays, the amount of non-driving-related content increases and may contain, for example, music control, phone book and calling functions.

External HUD devices such as the Navdy [84], Garmin [52] or Pioneer's NavGate HUD [97] are additional devices to place below the windshield. Similarly, the smartphone can be used as HUD by means of applications such as the HUDway [43] or the Navier HUD Navigation. These external HUDs are usually of a smaller size but can display more diverse content. The Navdy HUD seems to be the most comprehensive one and provides many smartphone related functions such as music control, messaging, phone call control and appointments.

3.2 Safety Risks & Benefits

The risks and benefits of HUDs are commonly studied by comparing it with an equivalent head-down display. Researchers found the HUD as superior in many aspects. Drivers can switch faster back and forth between the road and the display [58]. The HUD lowers the reaccommodation time [21] and demand. While this advantage is small for young drivers [129, 130], it alleviates the effort for elderly drivers [53]. Drivers can focus more on the road (increased eyes-on-the-road time) [50, 58, 73] and hence have an higher awareness of the surroundings [54]. This results in a faster recognition of road events as well as display content [50, 73]. Moreover, drivers maintain a more consistent speed [54, 74], feel less stress [74] and load [50] and overall safer [113]. Yet, the HUD's benefits seem to depend on the situational workload [67], the complexity and design of the HUD interface [89] and of course the image quality and perceptibility [42]. These benefits are expected to be even more pronounced for elderly drivers due to their reduced reaccommodation abilities and speed [42].

However, HUDs can also occlude or clutter the road scene [46], hamper the perception of size and distance of real world objects [107] and increase the reaction times of drivers who already have slow reactions [124]. It may furthermore cause drivers to change their visual behavior [20]. Distraction phenomena such as cognitive capture and attention tunneling (related to inattention and change blindness) are associated particularly with the HUD. All of these phenomena lead to the same problem: The drivers are focused on the HUD, neglect the road scene and miss out on critical events, without being aware of the reduced attention and resources for driving as their vision is still directed towards the road scene [37, 55, 75, 90, 116, 132].

3.3 Objectives of Extending the HUD

Compared to the alternative, the head-down displays, HUDs are superior in many aspects. Information uptake costs less effort and time, resulting in an increased safety for the driver and other road users. Furthermore, drivers almost always prefer the HUD over head-down displays (e.g., [117]). Consequently, to further lower risks associated with the use of other displays it is only reasonable to advance the HUD and exploit its benefits. Therefore, academia and industry aim to extend the display's field of view and depth coverage – striving for a large-sized 3D windshield display. Such WSDs could host a larger amount and variety of content and allow new ways of presentation such as augmented reality, yet, the safety of such interfaces needs to be verified first. Research shows promising results in terms of safety as well as user satisfaction: Drivers react faster [32, 74, 93, 104], spend more time monitoring the road scene [4, 58, 81], drive at a more consistent speed [74] and find it easier to detect and be aware of road hazards [60, 78]. AR has further increased situation awareness [86], supported driving performance without increasing the mental workload [81, 113], induced less divided attention and errors [60] and reduced driver distraction [32]. It may also diminish aggressive driving behaviors as it can reduce the isolation and anonymity of drivers by, e.g., displaying interests shared with other drivers close-by [82]. A naturalistic AR view is assumed to lower the visual clutter and the cognitive workload [79]. Most drivers stated to prefer the AR view over conventional display approaches [100, 113] as it is more intuitive, accurate, clear, informative, helpful, interesting and less distracting [60, 93, 100]. These benefits are even more pronounced for elderly drivers due to their lower cognitive and visual abilities [60, 78]. Yet, elderly drivers are also more prone to overload [121]. Negative (long-term) effects and risks of AR WSDs may be over-reliance, behavior change (misuse), overseeing or ignoring real-world cues and cognitive capture (though these are reduced for conformal AR) [41, 86].

AR WSDs are expected to increase safety also on real roads. Nevertheless, Gabbard et al. [41] point at the need for further research as the impacts of augmented reality on the driver and safety are *'still largely unknown or not fully understood'*.

4

From Head-Up to Windshield Displays

This chapter positions our own research within related work. First, we outline the research field of windshield displays by means of the design space and briefly embed our own work within this context. Concurrently, we highlight the investigated subfields and point at the corresponding publications. In the following sections, we explain the relevance of these subfields more deeply and thereby motivate our research. We position our work within the specific related work and discuss the research approaches, methods and findings to derive future work.

4.1 Design Space

In HCI, design spaces are defined to provide an overview of a particular research field to new designers and researchers [83, 101] and a common basis for discussions [57, 83], to identify unknown aspects and underexplored directions [101] as well as new possibilities [24], implications and constraints [87], to help developing design variants and understanding their differences [24, 35], strengths and limitations [76] and to eventually classify systems within the framework [87]. As design spaces are defined for specific domains with individual goals, they also vary in form, dimensionality and structure.

Our design space is based on a literature review on head-up and windshield display applications of any development stage with particular focus on content and visualization. Similar to Rasmussen et al. [101] and Kern et al. [57], we performed a structured search and selection process to gather a fundamental set of publications of the field. We extended the resulting list by means of brainstormings and focus groups as explained below. The process of tagging, sorting and eliminating redundant findings showed that the fundamental idea was often tied to a particular user and scenario (context), visualization or interaction aspect. Their diversity and the requirement of different HUD and WSD characteristics motivated us to collect and structure those aspects in one design space (see figure 4.1).

Again, we distinguish the WSD from the HUD primarily through the extended coverage of the driver's field of regard (display size) and potentially the depth (3D). We identified the key differences but also the potentials for fluent transitions from the HUD to the WSD interface. The design space shows how these key differences create new or interrelate with existing design factors and thereby answers the question *what design opportunities do HUDs and WSDs provide? (RQ 2)*. Descriptions of all factors, supported by exemplary related work, are provided in the publication [P7]. Below, we embed our research in the design space and explain which *factors* we investigated. Figure 4.1 highlights the investigated (blue color) and broached (light blue pattern) aspects (cells).

User We considered the driver as single *user*, *observer* and *actor* in all studies. Yet, we propose the use of the windshield as public display and portray one exemplary use case for passers-by [P7].

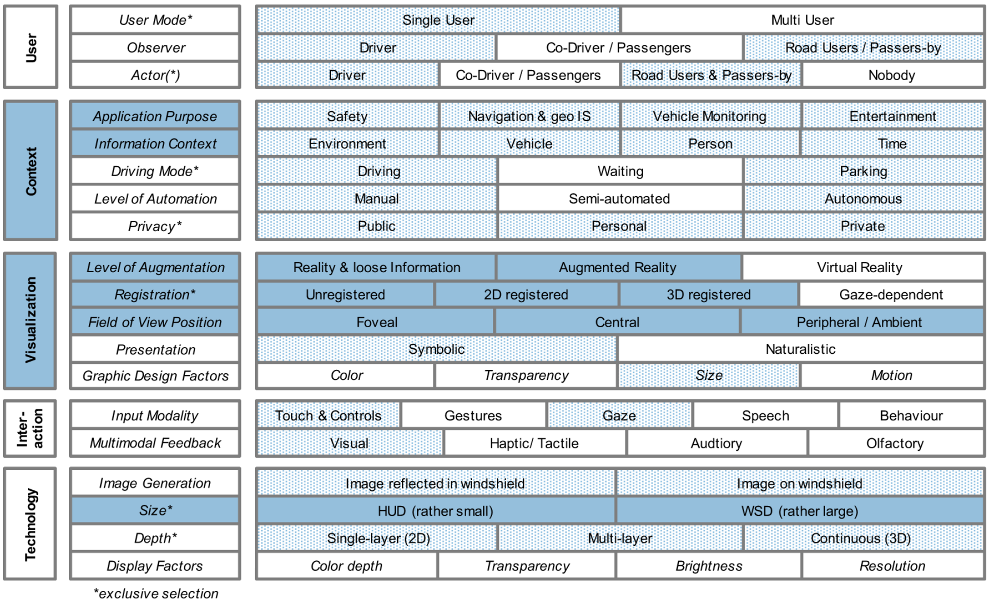

Figure 4.1: The design space shows factors that need to be considered when designing interfaces for the HUD or a WSD (see publication [P7] for detailed explanations). The research presented in this thesis focused on the factors and dimensions with blue background color. Cells with light blue pattern are broached in at least one study as side aspect. White cells are not explicitly researched.

Context We collected use cases, content and applications for the future windshield display and categorized those according to the *application purpose* [P7]. We developed and tested prototypes with a safety [P9], entertainment [P10] and monitoring [P2, P6] purpose. Additionally, the *application purpose* and the *information context* are incorporated in the view management concept [P1, P8]. We focused on the *mode* driving, however, most presented applications and concepts are also applicable to waiting and parking cars. Accordingly, we investigated primarily the manual *level of automation*. We outlooked on autonomous cars and suggested the HUD for the presentation of trust-supporting visualizations [P6]. As for the *privacy*, we consider and present content that is public, personal and private but did not examine one particular option.

Visualization The *level of augmentation* (later also called *stabilization*) was broached as a side aspect in many user studies (e.g., [P2, P10]), particularly the amplification of the reality with loose, detached information. We addressed augmented reality explicitly in [P1, P8, P9]. We used virtual reality to prototype 3D windshield displays but did not consider its use in the car. We researched the *registration* along with the *level of augmentation*. Unregistered content is a static placement (like loose, screen-fixed information) and is broached in every study as we regard it as the default placement option. It is explicitly examined when the conventional head-up and head-down displays served as a baseline for comparisons against 2D registration [P9] and head-stabilization [P2]. Also the view management concept looks into the different types of registration as well as *field of view positions* [P1, P8]. The field of view and the detection and response to stimuli at particular positions are often broached as side aspect to discuss and justify content placements [P1, P9]. We particularly addressed this topic in two studies about the location-specific response performance and stimuli sizes for large head-up displays [P5]. The *presentation* of content is symbolic in all studies. Apart of the *size* [P5] we did not examine any *graphic design factor*.

Interaction Interaction with the windshield display is not in the scope of this thesis. We conducted one study that compared *input modalities* for the superimposition of information on demand [P3]. As we focus on the windshield display as a visual output device, we researched the visual *feedback modality* only.

Technology The technology is part of our HCI design space as it interrelates with other aspects, for example, who can see the display (observer) or the possibility of registration. The realization of windshield displays is not part of this thesis's scope but considered for the development of prototypes. We *generated the image* behind the windshield (or combiner) in all studies and compared it with the display of the image on the windshield itself [P10]. The image *size* is regarded as a key factor that differentiates head-up and windshield displays and is therefore pronounced in all studies. We mostly targeted the larger windshield display and used the small head-up display in case of size limitations [P2, P6] or as a baseline [P9] . The display's depth coverage is another potential key feature but also a technological challenge of windshield displays. In most studies we investigated WSDs with a single layer. Multiple layers and continuous depth are examined in the view management concept [P1, P8]. We did not look into the *display factors* (see figure 4.1) as these depend highly on the eventual technological realization of a WSD.

4.2 Prototyping

For externally valid research on the HUD's safety, Gish et al. [42] impose the following requirements for the study prototypes: The image has to be visible through an optical (see-through) combiner to both eyes. It must be separated from the driving scene and displayed in a distance above 2.5 m. Furthermore, they require the setup to be integrable into a car, presumably, for follow-up real world studies. We overall agree with Gish et al. but as they are setting high expectations, we found that even fundamental HUD research rarely met these requirements. We also think they are not fully suitable for prototypes made to research the transition from HUD to WSD. As explained earlier, the technological realization of HUDs does hardly scale to the entire windshield (see section on *Technological Realization*) and so it is questionable if the WSD will be realized like a conventional HUD. Consequently, neither the WSD's coverage of the drivers' entire field of view nor the provision of 3D is guaranteed. We think it is worth to explore displays with varying coverage and dimensionality and stand back from the conventional HUD construction. The prototypes developed and applied as part of this thesis are situated between HUD and WSD (see figure 4.2). We are aware of the limitations of research utilizing prototypes that differ from the eventual display technology. However, without them we cannot start exploring such displays.

Gish et al. defined a categorization for HUD prototypes which suggests five setup types [42]: graphic HUD, projected HUD, binocular mirrored HUD, partial overlap mirrored HUD and monocular mirrored HUD. Since this HUD meta-review was published (in 1995), new prototyping possibilities appeared which motivated us to update their categorization (see table 4.1): Firstly, we will refer to WSDs instead of HUDs. The category *graphic WSD* remains as suggested. We extend the category *projected WSD* to gather all prototypes with projector-based image generation and omit the aspect of distance equality. Also the category of *binocular mirrored WSDs* remains unchanged, however, we emphasize that it includes both 2D and 3D variants. As we are not aware of a recent implementation of a *monocular mirrored WSD* (reflected image is visible to one eye only) nor of a *partial overlap mirrored WSD* (each eye perceives one half of the image) for drivers, we omit these variants. Furthermore, we add *see-through* and *non-see-through head-mounted displays* and *augmented virtuality (AV) simulations* to the categorization. The head-mounted displays (HMDs) and AV simulators are needed to fully study 3D WSDs as they enable an immersive experience and exploration of all depth ranges and sizes. Below, we briefly describe the image generation of the suggested categories as well as their advantages and disadvantages. They are explained more deeply in the *Appendix [A]* of this thesis. Furthermore, exemplary prototypes from related research are quoted and opposed to the prototypes which we developed and applied in our research.

Table 4.1: Variants of windshield display prototypes that we developed and applied in our user studies. Variants marked with an asterisk (*) are based on the categorization from Gish et al. [42], the remaining ones are contributed by us.

Prototype	**Description**	**Advantages (+) and Disadvantages (–)**
Graphic WSD*	2D WSD image and driving scene are displayed through the same technology (usually a large display) and hence at the same distance	(+) easy to realize and low-cost (–) no studies about oculomotor mechanisms (vergence & accommodation)
Projected WSD*	2D WSD image is displayed through a projector on the windshield, screen or wall	(+) easy to realize and low-cost (–) often a slanted image and low distance (–) no studies about oculomotor mechanisms
Mirrored WSD*	2D or 3D WSD image reflected into the windshield; driving scene and image are typically at separated depths	(+) similar to conventional HUDs (+) enables studying oculomotor mechanisms (–) compromise between image distance and setup size / complexity
See-through HMD (AR glasses)	Head-worn device presents the WSD image as a transparent overlay to the real world (head-stabilized by default); monocular, binocular, 2D and 3D versions possible	(+) enables research about 3D, depth and oculomotor mechanisms (+) usable in real cars (–) tedious realization of (conventional) car-stabilized content (–) often a small visual field (no periphery)
Non-see-through HMD (VR glasses)	Head-worn device presents both 3D WSD image and driving scene (immersive simulation)	(+) enables research about 3D and depth (–) no perception of self and surroundings (–) limited studies about oculomotor mechanisms
AV Simulation	3D WSD image and driving scene are displayed through a large projection system (immersive simulation)	(+) enables research about 3D and depth (+) perception of self and surroundings (–) limited studies about oculomotor mechanisms

These prototypes facilitate researching variations of the two key differences, size and depth. In studies that focused on vision and safety, we applied setups that are similar to the conventional HUD, potentially with a larger size and unless depth perception was required. To research the depth aspect, a 3D-capable prototype was required. Below, we explain the prototype that we found to provide the best opportunity to study and experience full-size 3D WSDs, *AV simulations*, more deeply.

Augmented Virtuality Simulations are often wall-projections that cover the entire FoV or even surround the user like in situation rooms (such as the CAVE or the AlloSphere). These simulators are highly complex to develop and costly. But as they present a 3D virtual world with sound depth perception, they enable a realistic experience of the look and feel of a full-size 3D windshield display. In contrast to the more common VR glasses, drivers can perceive themselves as well as the the car mockup and are relieved from the (heavy) VR glasses. The situation rooms also feature a higher focal distance (which comes closer to driving) but the user may still suffer from a vergence and accommodation conflict. Due to their complexity and costs, AV simulators such as the CAVE are rarely applied for driving simulations (for example, [56, 66, 72]). We used the AlloSphere, a near-to-spherical situation room, for our research about 3D information layouts [P1]. Both a real driving scene and the augmenting WSD content are displayed through the projection system and framed by a car mockup to obtain an immersive, realistic experience (see (4) in figure 4.2).

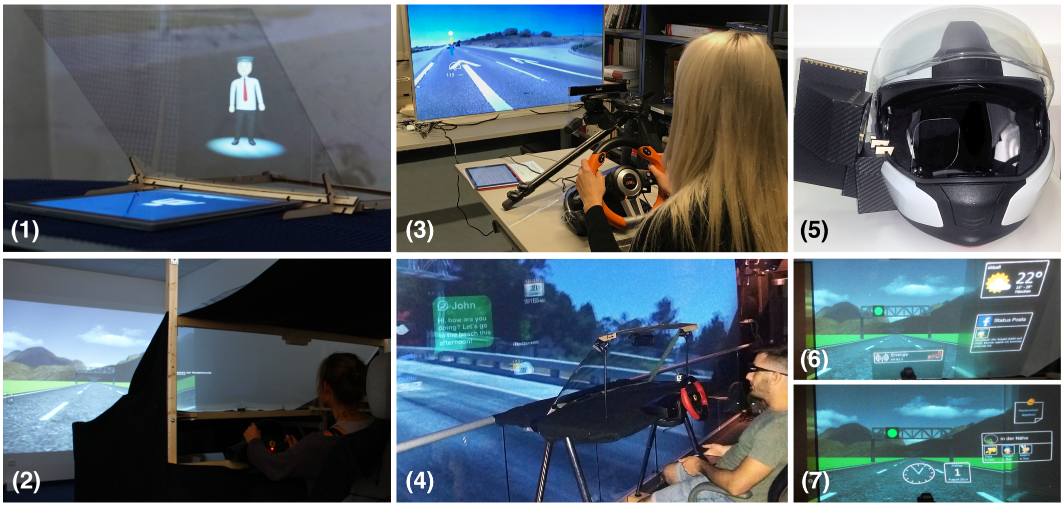

Figure 4.2: Exemplary prototypes which we utilized in our user studies. The images show the following prototype variants: (1), (2) and (7) mirrored WSDs, (3) graphic WSD, (4) AV simulation, (5) see-through HMD, (6) projected WSD.

4.3 Display Content

In-car displays, particularly the central information display (CID), present a large amount and variety of information to the drivers (see [117] for examples). Head-up displays present primarily driving-related information. Drivers also often use their smartphones to access driving-related but also unrelated content while driving (see [P4] for details). However, more than 80% of all accidents are associated with this behavior [16, 51]. An extended display space could host a larger amount and variety of information. The HUD's safety benefits, such as the enhanced information uptake, suggest to transfer content from other, less safe in-car displays or brought-in devices, such as the smartphone, onto the WSD, as also suggested by other researchers [120]. But badly placed and excessive amounts of information can attract the driver's attention, clutter the view and hamper the perception of the road scene, which results in a distracted driver [41, 42, 95]. Consequently, superfluous content has to be avoided also on the windshield display. Accordingly, we pursue the questions *which content could be presented on the windshield display? (RQ 1)* and more specifically *which of the potential content do drivers actually want to see on their own display?*.

Overview of Related Research Researchers started to explore the content drivers could imagine or want to see on their windshield. For example, Boström et al. [15] identified a variety of potential HUD information by means of brainstormings, interviews and focus groups. Park et al. [94] studied gender-specific content preferences. Tretten [117] asked drivers in an online survey which driving-related and non-related content they would like to perceive at which in-car display. He also let drivers experience a HUD in their own car to later interview them about their content preferences.

Table 4.2 summarizes the results of these studies and shows that drivers are mainly interested in driving-related content [15, 94, 117]. Many drivers use their smartphone while driving and other researchers showed that they expect the in-car displays to host this content in thefuture [47]. Yet, these studies found drivers to be reluctant to select such content [15, 117]. The participants of Boström et al. [15] were strictly against mirroring the smartphone on the HUD as they were concerned about information overflow and disturbance as well as the HUD's spatial limitations. Rao et al. [100] also mentioned that their participants were concerned about information overflow and superfluous content (after experiencing an AR HUD). Similarly, Tretten [117] assumes that his participants selected items which are monitored and responded to quickly because they impose low cognitive workload and are well-practiced – which generally excludes all novel (and non-driving-related) content.

Research Need However, in these studies participants could often only choose from the provided set of information and did not have the opportunity to contribute own ideas and add the desired items (e.g., non-driving-related content). Furthermore, they focused on the small HUD and did not consider a windshield display. Given the larger and 3D space, it is questionable whether participants would like to perceive the same variety of information.

Table 4.2: Content that drivers would like to see on their personal windshield display (minimum 5%). Drivers are primarily interested in driving-related content. They have diverging opinions regarding non-driving-related content but it seems that the desire for such content is growing.

Häuslschmid et al. [P1]		**Park et al.** [94]	**Tretten** [117]
Survey:	***Post-Study Questionnaire:***	***User Study:***	***Survey:***
navigation (81%)	navigation (100%)	navigation (100%)	road image (48%)
fuel & battery (68%)	speed (100%)	speed (95%)	sport shift (48%)
head way (52%)	road hazards (96%)	traffic info. (50%)	speeding (45%)
traffic&street sign (52%)	car status (96%)	vehicle info. (30%)	park support (43%)
music control (50%)	time & date (87%)	messages (20%)	lane changes (41%)
phone calls (47%)	headway (78%)	lane change (15%)	
vehicle status (40%)	POIs (78%)	headway (10%)	***On-road Study:***
music selection (42%)	calls (74%)	time (5%)	warnings (43%)
messages (31%)	entertainment (74%)		navigation (35%)
economy drive (26%)	appointment (74%)		traffic info. (25%)
POIs (19%)	messages (70%)		speed limits (18%)
garage opener (18%)	weather (61%)		speedometer (15%)
public transport (11%)			other driving-related content (13%)
inter-driver comm. (10%)			multimedia (13%)
work & tasks (8%)			speed only (10%)

Our Research Contribution We researched the potential and desired content for windshield displays in a three step process: At first, we searched HUD and WSD literature and patents for use cases, features, application ideas and particular content suggestions [P7]. Next, we extended this list by means of brainstorming sessions and focus groups in which we asked drivers about the content they regard as useful and desirable [P7] (similar to Boström et al. [15]). We obtained a set of 211 individual ideas, use cases, applications and features. Lastly, we conducted an online survey about the information drivers access on the smartphone while driving and the content they want to perceive on their personal WSD [P1] (similar to Tretten's online survey [117]).

Table 4.2 presents the content our drivers would like to perceive on their personal HUDs. We further found that most of our participants limited the WSD to approximately six items [P1, P7], which might be related to the concerns about information overflow as mentioned in related research. Our drivers also consistently prioritized driving-related content, which is in line with prior research, but they did choose more non-driving-related content. In this regard, the survey showed a strong division of the respondents: Some of our drivers stated that they do not want to be exposed to non-driving-related content, particularly social media and messages, while driving. Other participants requested the display of smartphone content and all of its notifications on their WSD explicitly [P1].

Conclusions & Future Work Related as well as our own research showed that drivers can imagine a large variety of content for the windshield display. However, when imagining the content of their personal display, the preferences in regard of amount and type differ strongly between individuals, user or consumer groups [61], cultures [117] and potentially even between genders [94]. Overall, drivers consistently prioritized driving-related content. Compared to the findings of related work, our participants desired more non-driving-related content [15, 117] but they were also given the full windshield area for information display (instead of a small HUD) which diminished the space limitations that some of the drivers mentioned [15]. Furthermore, they were not limited to a pre-defined set of (mostly driving-related) content. Through the years, the smartphone became indispensable for the young drivers and the desire to be always online and connected grew, causing its use while driving.

Today, drivers are used to adjust their devices such as the smartphone to meet their personal requirements [106]. They seem to expect their cars to become personalizable [115] and to host smartphone content [47]. Nevertheless, drivers are concerned about information overflow and avoid content which is not interesting for them or relevant for driving [100, 117]. Accordingly, superfluous information has to be avoided to keep distraction at a minimum. This points at the need for personalization of the WSD content. Although Gish et al. [42] identified this need already more than 20 years ago and other researchers confirmed it (e.g., Tractinsky et al. [115]), personalization of in-car displays is still at an early stage and limited to head-down-displays. We expect that letting drivers configure the content of their windshield displays – within safety boundaries – could enhance user satisfaction and possibly also safety. The WSD interface may provide a set of pre-defined and safely designed items from which the driver can choose (a limited amount). This item set might incorporate the drivers' desires summarized in table 4.2. Whether or which non-driving-related content should be provided is still to be researched. So far, too little research (e.g., [26, 127], [P10]) has been carried out to investigate its impacts on the driver. As we do not know yet how intensively drivers would engage in reading such content, more research is needed to get a deeper understanding of potential safety impacts.

4.4 Information Perception

The HUD is placed close to the driver's regular line of sight as this location is favored by the drivers and promotes fast information uptake [120, 137]. Immediate recognition enables fast reactions (corresponding to high response performance) and are hence highly important, particularly for safety-relevant information. The widely-accepted and applied SEEV model suggests that the probability of the driver shifting his or her attention to a particular object depends on the *salience* of the object (visual conspicuity, e.g., contrast or motion), the physical and mental *effort* to visually focus on the object (depends largely on its location and eccentricity, respectively), the *expectancy* of changes at a specific location (depends on the frequency of changes) and the *value* as drivers generally seek relevant information (depends on the relevance of the object's location) [39, 133]. As the model shows, the uptake of a stimulus (simple graphical item) at a specific location depends largely on its location. The extension from HUD to WSD is motivated by the opportunity to place information across the entire windshield. For a safe information placement, we need to consult the drivers' response performance at the contemplated locations. This need motivated us to identify *which windshield display locations promote fast responses? (RQ 3)*.

Overview of Related Research Table 4.3 provides a quick overview of relevant research about the drivers' response performance at specific locations in the windshield area. It contrasts factors such as the stimuli, display prototypes, tasks, fields of view and chosen locations of related research to our own work. These studies showed that the drivers' response times are lowest within an area of 5° around the line of sight, with a slight advantage of positions below and to the right of the center (e.g., [120, 134, 137]). Outside of the central area the response performance seems to deteriorate consistently towards higher angles (within a FoV of $20° \times 10°$ centered around the line of sight) [110]. The studies of Lamble et al. [65] and Wittmann et al. [134] suggest that the visual field has an elliptical shape and deteriorates slower in the horizontal direction. However, the degree of the performance loss is still vague due to the large number of influencing factors and a deficiency of comparable and systematic measurements at peripheral positions (while driving).

Research Need Drivers can react within less than one second – which points at the need to control the influencing factors in order to obtain precise response time measurements. As table 4.3 shows, the related studies differ greatly in all of the mentioned factors. For example, the design and overall size of the stimuli influence their saliency and in turn how (fast) it attracts the driver's attention [33, 42, 44, 108]. The images of the applied prototypes and driving simulators differ, for example, in quality and distance. As explained earlier, this influences the driver's perception and particularly the oculomotor mechanics as well as the response times. It has to be noted that neither of these setups fulfills the requirements for HUD vision research from Gish et al. [42]. Also the applied tasks, their simulated attention allocation strategies and so the visuomotor behavior vary considerably [134] which makes the performances in both primary and secondary tasks incomparable across the studies.[1] Most problematically for the WSD, the drivers' response performance was not investigated systematically across the entire windshield area (a homogenous set of locations), as also pointed out by Tsimhoni et al. [120]. Only few specific locations have been investigated thoroughly (see table 4.3).

[1] The detection-response task places the primary task (driving) in focus of visual attention and simple stimuli have to be detected as secondary task. The monitoring task forces the driver to visually attend to the HUD and leaves the complex driving task to be executed with peripheral vision. The first scenario happens presumably more often in real driving but the strength of the second scenario is that it provides insights into the impact of reading information from particular locations on the driving performance. The two scenarios require a considerably different visuomotor behavior [134].

We are not aware of a user study that provides systematic and comparable measurements within the peripheral FoV or even better across the entire windshield. Vision research looks into these areas, however, in completely different settings, which are not (directly) transferable to the driving situation (e.g., [33, 44]).

The differences in the single factors can have strong influences on the results which raises the question if the findings of the quoted studies are generalizable. Furthermore, they tested rather small fields of view so we can barely draw conclusions about the information perception in the periphery. Based on these studies, we cannot overall assess the driver's location-specific perception and in turn design a well-informed and safe WSD interface.

Our Research Contribution To gain deeper insights into the drivers' information perception across the windshield, we performed two consecutive user studies with a medium-size, mirrored WSD. This study tested 17 positions within an extended visual field of $35° \times 15°$ [P5]. In addition to the response times, this study delivered small, well-legible stimuli sizes which we interpolated to a model for sizing recommendations. We furthermore conducted one user study with a full-size 3D WSD in an AV simulator [P1] which tested a set of 48 positions across the entire windshield and a depth range of 19.1 m.

Our response time measurements are overall in line with the findings of prior work: We found the fastest responses at the locations 5° to right and above the center [P1, P5]. The response performance declined in an elliptical shape. The response times increased towards higher angles, comparing the three fields of 0–5°, 5–15° and 15–25° [P5]. The detriment of locations above approximately 15° is also apparent in our study about the detection of road hazards (moving stimuli) [P9]. Our AV simulation study showed a correlation between response time and eccentricity. It furthermore showed a considerable decrease in response rate towards higher angles, which could correspond to a very slow response time when drivers are given more time [P1]. More details can be found in the corresponding publications [P1, P5]. Comparing the location-specific response performances of our three studies, the results are surprisingly consistent, suggesting high validity.

Conclusions & Future Work The response times (and the derived sizing model) are important for the design of safe WSD interfaces. To minimize distraction, information needs to be displayed in legible sizes and at well-perceptible locations. However, many factors such as the drivers' characteristics (e.g., age [108]), the situation (e.g., demand [135]), the display (e.g., brightness [42]) and the stimuli (e.g., contrast [108]) influence the drivers' perception of WSD stimuli and complicate the provision of the basic values.

Based on the existing studies we cannot draw precise conclusions about the drivers' response performance. Our three studies systematically tested a large set of locations and extended visual fields and thereby provide comparable measurements, also at larger angles. The results of our studies are overall consistent and in line with prior research. Within the tested area of $20° \times 10°$, the response times measured by Tsimhoni et al. [120] are comparable to ours. The participants from Yoo et al. [137] reacted overall faster although these two studies are very similar, which again shows the influence of the study factors.

Our studies indicated that the drivers' response performance decreases at an angle around 15°. This might be caused by the increased effort, as the SEEV model suggests, but could also be related to the biological structure of the eye (rod and cone cells) as well as the drivers' visuomotor mechanics [103]: Drivers fixate stimuli at an angle below 15° through eye movements and beyond through head rotations. The delay and lower speed of head motions suggest faster switching times (and in turn faster responses) below 15° and, consequently, to place the WSD content inside of this field. However, drivers do not mandatorily have to fixate a stimulus for recognition, provided it is large enough [109]. But it is still unclear whether drivers recognize stimuli through fixation or peripheral vision and if this is consciously controlled [70, 102]. The drivers' visual behavior and reflexes are related to the distraction mechanisms (see publication [P4]) and relevant for the interface design: For example, a peripheral (AR) stimulus might be related to a crossing pedestrian (hazard) or a point of interest (non-hazard). The annotation may draw the driver's attention and gaze (this might depend on the stimulus' recognizablility with peripheral vision) away from the driving task which could be beneficial for safety in the first example but dangerous in the second one; the driver's consciousness of this behavior plays an important role as a controlled attention shift allows the driver to decide whether the situation allows for it, while an unconscious shift happens independently of the situation. Hence, more in-depth eye-tracking studies are needed to understand the drivers' visual behavior and reflexes. Furthermore, future research needs to examine the influence of the above mentioned factors as well as depth systematically to obtain performance and size estimations which facilitate the design of safe interfaces which are suitable for all drivers and situations.

Table 4.3: Overview of studies that measured the drivers' response performance at particular locations. The column *locations* describes the count of WSD positions and the FoV. Studies marked with (*) investigated diverse positions within the car's interior. The relevant locations refer to the HUD (5°), above the dashboard (4°, 6°), above the center stack (17°, 24°) and the rear view mirror (27°, 42°, values are approximations). The column *tasks* refers to the primary (1) and secondary task (2).

Researchers	**N**	**Stimuli**	**Locations**	**HUD**	**Tasks**
Tsimhoni et al. [120]	16	names	8: 20° × 10°	mirrored WSD	1. driving curvy roads 2. detection-response task
Yoo et al. [137]	24	triangle	15: 20° × 10°	mirrored WSD	1. detect events in videos 2. detection-response task
Wittmann et al. [134]	30	bar & number	4*: 5°, 6°, 17°, 27°	projected WSD	1. lane positioning 2. monitor and react to display
Lamble et al. [65]	12	braking lead car	5*: 0°, 4°, 17°, 24°, 42°	LED display	1. similar to car-following task (detect decelerating car) 2. monitor and react to display
Häuslschmid et al. [P5] (2 studies)	24, 22	shapes, names	17: 35° × 15°	mirrored WSD	1. lane change task 2. detection-response tasks
Häuslschmid et al. [P1]	12	shapes	48: 63° × 23°	VR room	1. ConTRe task 2. detecion-response task

4.5 Information Placement Strategies

Current HUDs are restricted to display few pieces of information inside a small 2D area (*screen-fixed placement*). Although no suitable commercial products are available [41], car manufacturers and suppliers already advertise with augmented reality HUDs. AR is one key motivation for the extension of the HUD. However, the annotation of the driver's view with digital information (*registered* *placement*) is only reasonable for content that is actually related to an object in the real world. Since some of the most important functions such as the speedometer do not suggest a registered placement, the classic screen-fixed placement will not become obsolete but needs to be combined with other placement strategies. In this thesis we differentiate three major strategies for information placement:

(1) Augmented reality – *world-stabilized* content – suggests to superimpose information spatially registered (in three dimensions) to the related real world object and to thereby extend their world [3]. Other common terms for this placement strategy are *registered*, *world-fixed* and *contact-analog* or *conformal*, though, the latter two require a naturalistic presentation (instead of a symbolic design) [41, 114].

(2) The content of the classic in-car displays and the conventional HUD is *car-stabilized* as it is displayed on a defined screen which is positioned at a fixed location within the car's interior and dissociated from the real world (also known as *screen-fixed*) [41].

(3) The *head-stabilized* placement refers to the fixation of content at one location within the user's FoV [68]. Accordingly, the content moves along the driver's head. Similarly, content can be stabilized to the user's eye gaze or other body parts.

Although researchers have highlighted its necessity [41, 42, 114, 128], it appears that a comprehensive placement approach for the extension from HUD to WSD has not been researched, yet. To thoroughly approach this problem, we first look into the different placement strategies to answer the question *which placement strategies are suitable for the windshield display? (RQ 5)*. We then combine the suitable strategies in a comprehensive view management approach (see section on *Information Placement*).

4.5.1 World-fixed versus Screen-fixed Placement

While certainly not all content is related to the outside world and hence suggests an AR placement, all information could be displayed inside a defined display area which is dissociated from the driving scene (as current HUDs do). Yet, academia and industry research intensively on augmented reality for drivers as both safety and sale benefits are expected. Research showed that world-fixed content can have various benefits for the driver compared to screen-fixed or no display support (see section on *Objectives of Extending the HUD*). Nevertheless, Gabbard et al. [41] emphasize the need for further investigation as *'the effects of AR information on driving performance, safety and mental workload are still largely unknown or not fully understood'*.

Most AR studies examine applications that are designed to support the driver, for example, in navigation [4], lane keeping [25], head way control [27] and perception of the surroundings (e.g., hazard detection [59, 98] and POIs [14]). Most of these applications make use of the central windshield area only. As we are interested in the transition from HUD to WSD and its size and coverage of the peripheral FoV is a new feature, we focused on the drivers' perception of the surroundings with special attention to the periphery. In particular, we studied the support of registered and screen-fixed annotations in detecting hazards [P9].

Overview of Related Research Hazard Warnings are studied, for example, by Charissis and colleagues. In low visibility scenarios, the drivers had to avoid collisions with the lead car. Charissis [25] presented cues for lane boundaries, lead and neighbouring cars and traffic congestions and showed that drivers caused 75% less crashes and maintained a larger headway. Traffic congestion and sharp turn warnings resulted in a crash reduction of 32.5% [27]. However, it is difficult to assess the meaning and validity of their findings as most of the reported results represent one participant only. With an equivalent goal, Kim et al. [59] and Pomarjanschi et al. [98] displayed registered pedestrian warnings on a HUD and compared it to the driver's performance without display support. Kim et al. [59] additionally tested screen-fixed warnings and showed that both HUDs improved the driver's performance but the AR-like version led to a smoother braking behavior than the conventional HUD. Pomarjanschi et al. [98] found that the mark up reduced the eye movements, reaction times and collisions, resulting in safer driving.

Research Need These studies indicate that world-fixed content is superior to screen-fixed information, however, they focused exclusively on the area directly in front of the driver. Researchers have diverging opinions about the required size of the AR FoV: Ng-Thow-Hing and collegues [86] argued that AR is not needed across the entire windshield as peripheral annotations will move out of the windshield area fast and leave little time to react to it, which would make them superfluous. Bark et al. [4] and Langlois et al. [66] proposed a FoV similar to the human eye but at least $20^\circ \times 10^\circ$. Gabbard et al. [41] suggested that an AR WSD should cover the entire FoV.

Our Research Contribution We compared 2D-registered hazard warnings within a horizontal range of 35° (WSD in 2 m) with conventional screen-fixed warnings (HUD in 2 m) and with the driver's (unsupported) detection of hazards [P9]. Primarily, drivers had to follow a lead car with constant head way (car-following task). Additionally, they had to detect soccer balls that were rolling towards (hazard) or away from the own lane (non-hazard) and to respond with button presses, similar to a detection-response task. We could not prove a faster reaction to augmented hazards than for the screen-fixed support but confirmed the increased *eyes-on-the-road* time shown by other researchers [4, 58, 81]. Drivers had a reduced visual search and spent on average 1.5 s longer monitoring the lead-car. More details are provided in the publication [P9]. According to the participants' feedback, the WSD was preferred and supported them best in detecting hazards.

Conclusions & Future Work Overall, our own and the related research showed that a world-fixed placement is superior to the screen-fixed equivalent in terms of safety and user satisfaction. The need for AR seems apparent but its characteristics are still to be determined. Researchers utilized prototypes of varying fidelity, size and depth coverage, ranging from graphic WSDs [98] to (3D) augmented virtuality prototypes [25]. This is reasonable since the characteristics of future WSDs are unknown and researchers disagree on the required size of the AR FoV. By now, most of the AR studies focused on the drivers' central visual field, covering the road ahead. We extended the AR area to exceed the minimal requirements ($20^\circ \times 10^\circ$ as suggested by [4, 66]) and annotated central as well as peripheral hazards and buildings. The drivers detected peripheral hazards in about the same time but their vision was more focused on the road scene ahead when hazards were directly annotated instead of hinted by screen-fixed warnings on the HUD. We conclude that an AR WSD is beneficial for the driver and safety. Furthermore, we argue that the FoV should cover the entire or at least large parts of the windshield. Future research needs to investigate the augmentation in peripheral FoV more deeply, potentially along with the driver's visual behavior and reflexes (as mentioned in the prior section on *Information Placement*).

Similar to the AR FoV size, researchers also discuss the need of a registration in depth: Ng-Thow-Hing and colleagues [86] think that a separation in depth may be beneficial as it supports visual search due to increased clarity and legibility [96]. In contrast, Gabbard and colleagues [41] think that such separation raises safety concerns. However, we are not aware of a study that compares 2D and 3D AR for drivers directly and supports one of these arguments. As 2D registration may be easier to technologically realize, future research should delineate the depth requirements.

4.5.2 Head-stabilized versus Screen-fixed Placement

With the growing market and distribution of AR and VR glasses, head-stabilized content is becoming more popular. Yet, until now see-through glasses have been utilized only sparsely in the automotive area. As head-stabilized content remains always within the FoV and at a fixed position, its recognition is highly probable even when the driver looks away from the road [69]. This may suggest increased safety in critical situations. But head-stabilized displays are more prone to clutter and to occlude the driver's sight [68] than the WSD as the FoV is smaller and head motions cannot alleviate the problem.

Overview of Related Research Lauber et al. [68] compared see-through glasses (head-stabilized) with a classic HUD (screen-fixed). They did not find statistically significant differences in the driver's reaction time to speed limit and collision warnings. Drivers rejected the head-stabilized content and favored the HUD due to its steadiness, spatial stability and higher quality. In a later study, Lauber et al. [69] showed a significantly better response time to head-stabilized warnings when the area for warnings was marked. Nonetheless, drivers preferred the HUD. Jose et al. [54] displayed speed, gear and route guidance information on a HUD, a HMD (head-stabilized) and a classic HDD, by means of VR glasses. The participants made fewer errors, maintained a more constant speed and detected the most pedestrians in the HUD condition. However, the difference between HUD and HMD was not as pronounced as between HUD and HDD. The drivers preferred the HUD over the HDD as the downward glances are unnecessary. The HMD image was displayed in the same distance but above the straight line of sight and received the lowest ratings.

Research Need Due to the issues mentioned above, we do not consider the use of see-through head-mounted displays for drivers as worthwhile. Yet, a head-mounted display might be useful for motorcyclists since reflecting an image into the motorcycle's windshield is problematic, riders are obligated to wear a helmet (to which the HMD can be attached and which already limits the FoV) and have a strong need as they are exposed to high risks. Currently, a lot of effort is invested into the development of helmets equipped with a see-through display. Yet, their actual risks and benefits have rarely been researched (see [P2]).

Our Research Contribution We developed a monocular see-through head-mounted display based on a conventional smartphone which is attached to a motorcyclist's helmet [P2]. In a riding simulator study, we compared the head-stabilized display with a standard head-down display (screen-fixed). To better inform riders and support a realistic assessment of the situation, riders were provided with speed, speed limit and curve information (including warnings). The HMD reduced workload and speeding. Our participants preferred the HMD over the HDD and found it more attractive, safer and easier to perceive information. Nonetheless, most riders were not interested in curve warnings and wanted speed information only.

Conclusions & Future Work Although head-stabilized warnings can improve the driver's reaction time, we think that they bring along too many disadvantages and risks. Yet, a head-stabilized display for motorcyclists seems to be promising and could become an equivalent to the driver's HUD. Future binocular helmet-mounted displays may provide depth and a large FoV and eventually AR. Yet, we do not recommend to extend its content to, for example, smartphone applications as it will possibly become true for the WSD. The motorcyclist's limited FoV is prone to clutter, occlusion, overload and distraction phenomena such as cognitive tunneling, resulting in risks outweighing the benefits and consequently severe safety concerns.

4.5.3 Placement Strategies suitable for WSDs

HUDs are just now setting out from 2D display spaces. Screen-fixed placement has been the default and will remain relevant in the future simply because most content has no relation to the outside world (unsuitable for registered placement). For the tested scenarios and applications, world-fixed placement seemed to be the better alternative. However, the type and amount of content displayed in these studies was limited and we cannot anticipate how several different items such as points of interest, route guidance and warnings will affect the driver. Several virtual objects moving around the scene might be overloading and highly distracting, as the study of Rao et al. [100] indicated. It remains to be researched how many resources will then be left for the timely perception of urgent information.

Head-stabilization could draw the driver's attention when not looking at, e.g., a danger or through the windshield (in case a head-mounted device is used). However, at the moment we cannot imagine a scenario in which head-stabilization, particularly when realized through head-mounted devices, is the most suitable solution. We hypothesize that the screen- or world-fixed information in combination with other communication channels, e.g., auditive or haptic feedback, draws the drivers attention just as well as head-stabilized information, without being limited by the system's and driver's field of view. This hypothesis needs to be examined in future work. As the first placement strategy may interrupt the driver and gain attention and the latter could guide the attention, a combined approach is conceivable. Future research has to incorporate audio warnings since these can effectively draw the drivers' attention, independently of where they are looking at, and warnings should use as many channels as possible, as proposed by Bubb et al. [19].

4.6 Information Layout

In the previous chapters, we learned that the drivers' ability to detect, recognize and respond to information across the WSD varies and depends on the information location. Badly designed windshield display interfaces cause the drivers to be distracted, meaning that they devote less perceptual and attentional resources to the road as potentially needed (more details can be found in [P4]). Well-known design problems of WSD interfaces such as occlusion, clutter and overload [41, 95, 100] are linked to the placement of content. As Dingus et al. [31] already pointed out, the placement of the single items on the WSD and the resulting arrangement need to be considered wisely to minimize distraction.

We also learned, that the WSD content is of varying importance for the driving task and the driver. For most of this content, there is no obvious location within the 3D space of the futuristic WSD.

For example, the speedometer, the music control, or an incoming message are features that are used frequently but do not suggest a location on the windshield display themselves. But *where should (such) information be placed (RQ 4)?*

As suggested by the *ecological interface design* framework [22, 122], we first approached the *work environment* to design a concept that is perceptually adequate and supports effective and natural information uptake. The framework suggests to then approach the users' *cognitive processes*, particularly when the *goal-directed behaviors are highly affected by dynamic environmental constraints* as it is the case for car drivers. Accordingly, we incorporated their placement preferences and layouts. We close this process by comparing the obtained layout variants and pointing at the need for revisions and further investigation. In particular, we applied the following four major steps:

(1) We consulted vision research to identify locations which can be considered safe as they promote information uptake but do not interfere with the driving scene and task. We extracted 3D information spaces within the FoV and assigned content to those spaces. This step resulted in a one-fits-all concept for information layout (*view management*).

(2) We asked drivers to design their personal layouts in order to obtain locations and layouts which are liked and intuitive for the drivers and hence presumably promote a better user satisfaction (than a one-fits-all layout). We then extracted layout patterns and assessed the safety of the obtained *personalized* information layouts.

(3) We *compared* the one-fits-all with the personalized layouts in a driving simulator study to find out which of the two is the safer version (in regard of information perception).

(4) We point at the need for revision and further elaboration of the view management concept as well as future research.

4.6.1 View Management Concept (One-fits-all Layout)

Information needs to be placed at locations which promote fast and easy information uptake; meaning that the driver can detect appearing or changing information when focusing on the road scene and glances towards this information require little time and effort (see section on *Safety Risks & Benefits*). As we learned in the previous chapter, the visual perception suggests to place content at the central positions. Dingus et al. [31] point at the influence of the eccentricity on the switching time and suggest to place content as close to the center as *'is practical'*. However, these locations are also central for the driving task and WSD information cannot occlude or clutter the driver's view [50]. Both might hamper the tracking of the road situation and a failure or delay in detecting hazards. As follows, the WSD locations have to be chosen also in consideration of the road scene.

Overview of Related Research Currently, most interfaces on, e.g., the smartphone but also on the conventional HUD, are laid out by means of 2D layout patterns – which are not (directly) applicable to a 3D WSD. The WSD may cover the entire windshield but (permanently visible) content needs to be scattered around the driving scene to avoid occlusion. A view management concept summarizes such criteria and rules and suggests particular locations and strategies for information placement. View management is largely researched in the area of see-through HMDs (e.g., [5, 105, 112]). These approaches focus on the world-fixed positioning of annotations which ensures that both world and content are well-perceptible. This is certainly highly relevant for AR content on the windshield display, but does not provide a solution for content without a relation to the outside scene. Consequently, a placement strategy that combines screen-fixed with world-registered content is needed (head-stabilization is excluded as explained in the section on *Information Placement Strategies*).

Lindemann et al. [72] and Lauber et al. [68] approached a multi-stage view management concept for the driver, however, they did not integrate these placement strategies either. Lindemann et al. [72] suggested an interface that displays mainly driving-related content on the windshield's bottom edge or as an overlay to the car's interior. The authors discussed the aspects of content stabilization (head and car), the canvas shape (flat and spherical) and the layering (multiple layers with flexible distances) and showed exemplary interfaces. Furthermore, they suggested some basic guidelines, for example, to support the perception of urgent information by blurring the remaining UI. It is further proposed to pre-define the depth level of the information layers based on their relevance but to allow drivers personalizing them. Items can switch the depth layers according to its relevance, context and the driver's preference. Lauber et al. [68] proposed a view management concept for HMDs. The content is either stabilized to the driver's head or to the car – world-registered content is neglected. The FoV is subdivided like a classic border layout (based on cardinal points) and features slots for, e.g., permanently visible (driving-related) content or temporary, urgent warnings. The content is dynamically assigned to a slot and designed depending on the situation and the driver's head-motions.

Research Need As explained earlier, we do not consider a head-mounted display and head-stabilized placement as appropriate for drivers. The placement approach of Lindemann et al. [72] would most probably require a HMD to realize the suggested placements, like the concept of Lauber et al. [68]. Both concepts are at an early stage and not sufficiently supported with related work. The authors did not explain their methodology or the choice of locations and content. Furthermore, they did not incorporate the driver in the design process or evaluate the concepts. Based on the information provided in the publications, we cannot estimate the safety and user satisfaction of these approaches and so we do not regard them as appropriate view management concepts for drivers.

Our Research Contribution Our one-fits-all view management concept (see [P1, P8]) exceeds the related work by far. In addition to the classic driving-related information we regarded also unrelated content, such as entertainment or communication functions. We particularly consider the transfer of smartphone content to the WSD, as we hypothesize that accessing it on the WSD is safer. Our view management concept suggests several 3D information spaces that are tied to a specific type of content, e.g., safety-critical or personal information. We segmented the FoV in information spaces and assigned content based on the ideal that the response time should correlate negatively with the importance of the information. We classified the importance of information based on the safety-relevance, immediacy, task-relation and context of information, as well as the information complexity and frequency of access, as suggested by Kun, Treten and Tsimhoni et al. [61, 120, 117]. As explained later, smartphone users apply similar criteria when arranging their smartphone apps [12]. As for the locations, we identified areas which are close to the driver's line of sight but do not occlude the areas relevant for safe driving (based on visual scanning patterns). Simultaneously, we identified locations which are preferred by the drivers and promote information uptake by means of our own and related research about visual perception. We furthermore suggested several depth ranges based on the theory of proxemics [45]. Together, the areas and depth ranges create up to six 3D information spaces of which three are intended to be permanently visible.

Though more profound and backed up by related work, also our concept was a first draft which required further elaboration and safety evaluation. To iteratively improve our concept, we conducted a first formative study in which we asked drivers about their placement preferences after they experienced example 3D WSDs on a HMD (see next section). We included the basic layout preferences of drivers into our concept and decided to compare it with more sophisticated personalized layouts.

4.6.2 Drivers' Personalized Layouts

Personalization is a topic of increasing importance and spreading. For example, smartphones are so deeply personalized that they are considered as *'the extended self'* [106]. People are used to choose the content and arrange it within the display space (within boundaries) which increases personal attachment to the device [12, 77]. It is not surprising that users expect the car's interfaces to be customizable as well [40, 115]. So far, car interfaces provide only little freedom for customization, although, researchers pointed at this need already more than 20 years ago. The car should allow the driver to adjust the content as well as its location, activation, representation, rate and onset [42].

Earlier, we considered the personalization of the WSD content and the transfer of information from the personal devices to the windshield. The flexibility of amount and type of content requires a customizable arrangement, which we researched as part of this thesis.

Overview of Related Research & Research Need So far, researchers suggested to personalize, e.g., the depth layers or the activation (on/off) of an item, but looked deeper into the preferred HUD location, only. Tretten [117] asked drivers at which windshield location they would like to position their head-up display after using a very basic HUD showing the speed. Most drivers wanted the HUD close to the center of their attention but not directly in it. They placed the speedometer within

Figure 4.3: The upper left image shows how the applied view management (first version) could look like when content is displayed in every information space. The remaining three images show example layouts created by the drivers who participated in the AV simulation study. The images show 2D versions of the driving scenes in which the drivers had to place content.

an area of 5° around the center (69%) but mostly below it (57%). The remaining participants placed the HUD more between 10° and 25° to the left (19%) or to the right (12%) or the center. We are not aware of a study that investigated the placement of more than one piece of information on the WSD and hence we cannot draw conclusions about their layout preferences.

Since we consider the display of smartphone content, of which the layout is personalized, we looked briefly into related work about the users' app arrangement strategies. Böhmer et al. [12] found that most people personalize their phone layouts and revise it when the content changes (apps added or removed). Users arrange the apps primarily based on the frequency of use, importance and relevance (separation on pages, e.g., important apps are on the first page) as well as the context (related apps are grouped). Users may try similar placement strategies on the WSD, but due the several distinct factors such as the display size, depth (2D versus 3D), these strategies are not fully applicable.

Our Research Contribution We performed a formative study [P8] and a lab experiment [P1] to obtain insights into the drivers' placement preferences. The formative study collected the favored locations for abstract content. We found the areas for urgent warnings and car-related content to be well-confirmed. Furthermore, the results indicated that there are no locations and particularly no depth levels that feel natural to all drivers. As far as possible and reasonable, the results of this study were incorporated in the design of the one-fits-all layout.

The lab experiment utilized the AlloSphere, a near-to-spherical VR situation room. A car mockup (see *Appendix*) and 360° 3D driving scenes created a visual reference close to a real driving situation. Within several iterations and driving scenes, the drivers designed their personalized 3D layout. We requested the drivers to define location, depth and size for ten driving-relevant and non-relevant graphical items and to think aloud during this procedure. This task was not compatible with a driving task and hence executed as (single) primary task. It is not surprising that the drivers wanted to personalize their WSD interfaces and that these configurations differ strongly, also from our one-fits-all layout. Many drivers aligned numerous items along the bottom edge of the windshield which is considered a generally safe location. Thereby, the drivers placed the items lower than the conventional HUD area. Most drivers did not place the content in the central area or too close to the line of sight. These findings are conflicting with prior research about the drivers' favored HUD location, simply because the areas that were chosen the most by our drivers (the left and bottom edges of the windshield) were not provided in prior research [117, 120, 137]. These studies also often limited the choice to a small area and asked for one location instead of many.

Participants placed related content close to each other. This overall confirmed the context-specific areas of the view management concept. Drivers also placed items across the entire windshield and at driving-relevant locations (e.g., on top of pedestrians) – jeopardizing safety. We could rarely discern registered placements (intending an AR placement) and explicit depth choices – potentially because it is a new variable which they are not used to adjust (in 2D layouts) but possibly also because there is no such thing as an intuitive depth for digital information.

4.6.3 Layout Comparison

Overall, we assumed that the one-fits-all layout is safer, as it is based on vision research but rejected by the participants due to the desire for personalization. The personalized layouts would be preferred and may potentially foster similar information perception performance as the content is placed as liked but cannot be considered safe since driving-related FoV areas might be used. In order to investigate these hypotheses and understand the safety trade-off between the one-fits-all and the drivers' personalized layouts, we compared both variants in a performance-measuring simulator study.

Overview of Related Research & Research Need As both the view management concept and the personalized layouts are new approaches and exceed related work, we cannot position our work within related automotive research.

We re-invited the participants of the prior study and requested them to perform the same tasks with their personalized layout and our one-fits-all concept. We also utilized the same full-surround 3D setup as in the prior study. The driving was simulated by means of a medium-demanding ConTRe task and highly realistic 3D driving footage. Next to driving, participants had to perform a detection-response task with shape-based stimuli (decoupled from the content of the previously used items). To pose a high workload, the stimuli were scheduled in a high frequency at the locations of the personalized layouts or the view management concept, respectively.

Our Research Contribution Although we separated both studies by more than one week, some drivers still recognized their layouts. The drivers showed a higher response performance when using the view management concept. We found both types to be compliant with the ideal of high performance for highly important information. The response performance decreased towards higher angles, which is compliant with prior research, and also for locations at which less relevant information would be placed. This suggests, that the drivers did consider the importance of the content when they placed it, like when laying out the apps on their phones [12]. However, the content was also placed further away from the road scene. This means that the aforementioned trade-off between proximity to the line of sight (allowing for fast perception of the display content) and the occlusion of the road scene (hampering its perception) was not optimized in the personalized layouts – suggesting that there are safer approaches. For the view management concept, we cannot draw a conclusion about the balance of occlusion and proximity, but its design considered this interrelation.

The differences between the two layout versions may be smaller in a less demanding situation and with more realistic information update frequency. Our drivers found it difficult to respond to the stimuli while driving. They further assessed the driving task to be medium realistic and difficult which is confirmed by their performance. The detection-response task was designed to be challenging in order to identify even small differences, as suggested by Gish et al. [42]. From a methodological perspective, this research contributes a novel type of driving simulation. We merged the ConTRe task, which provides a high level of control and solid metrics, with footage of real driving, which is more realistic than a simulated world by nature. We think this type of driving simulation is suitable particularly for research about the driver's visual perception, especially when it comes to the perception of the world (for example, in AR and visual search studies). The impact of the de-coupling of the driver's actions and the scene on the realism and the comparability to 3D driving simulators needs to be researched in future work.

4.6.4 Conclusions & Future Work

We are concerned about the safety impacts of WSDs in general and the content arrangement in particular due to the aforementioned reasons such as overload, clutter and occlusion. Accordingly, we created a one-fits-all layout that is built upon vision research. Safety is the highest goal but there is demand to integrate all sorts of content. We assumed that personalized interfaces are more intuitive (the driver finds information at locations that seem natural to him/her and hence access information faster) but questioned their safety. Consequently, we collected customized arrangements for the same amount and type of content. We compared those layouts in a driving simulator study and found that the research-based layout was superior to the customized and presumably more intuitive versions.

Since some of the drivers are either not aware of the occlusion issue or disrespect it when designing the layout (resulting in unsafe layouts) we conclude that WSDs with a fully configurable layout cannot be considered safe. Yet, drivers want personalization and research utilizing other devices or interfaces showed an increased acceptance and satisfaction [12, 77, 106]. However, they also want to adjust these layouts frequently which is more alarming as this might prevent learning. If drivers apply the same behavior as with their phone, they will update the layout when content is added or removed from the display, which seems to happen at least once a month for experienced users [12]. The consistancy of the information location supports learning and so drivers may derive the importance of content from its location without glancing at it. Drivers may be alerted and react fast when content occurs at critical locations but ignore it at other locations. After all, this may increase the time and attention a driver devotes to the driving task and hence safety.

The overall goal of the view management concept is to minimize distraction and enhance the efficiency of information uptake. From our studies we conclude that the view management concept needs revision. As explained earlier, we need to apply an iterative and human-centered research approach, specifically when designing such safety-critical interfaces. In both publications [P1, P8], we identified needs for revision, further elaboration and future research. In the *Appendix [B]* of this thesis we present a revised version of our view management concept. An optimized view management concept could serve as a default layout which may be customized (within boundaries) by the drivers. We think further research is needed to investigate *at which windshield display locations content should be placed (RQ 4)*. Future research should consider a combined approach and let drivers design their own layouts within the safe areas. At the same time, the safety and usability of personalized WSD interfaces as well as their learnability should be addressed. Eventually, researchers need to look deeply into distraction and foremost into the cognitive tunneling and attention capture phenomena. It is of utmost importance that, even and particularly when the display is personalized, the content layout and design do not encourage or cause the drivers to be overly engaged in using it.

5 FUTURE WINDSHIELD DISPLAYS

Even during the time period that this thesis' research was carried out, substantial advancements were made in area of head-up displays but also in other, related fields. We think that two trends, autonomous driving and AR devices, may influence the future need and relevance of the windshield display considerably and that it may possibly decide about its realization, as discussed below. Yet, the car industry is investing heavily into the development of the windshield display, which already resulted in increased image sizes and depths. Below, we report the prototypes and showcases exhibited at recent technology fairs. In consideration of these trends and technological advancements as well as our own and related research, we forecast what the interface of the future WSD may look like.

5.1 Interplay with other Trends

Along with the windshield display, there are two major trends which will strongly influence the need for a WSD and its eventual realization: Autonomous driving as well as high-class AR consumer devices may make the AR WSD obsolete as the *user* might either be released from the driving task or provided with an omni-present display alternative.

Autonomous Driving Automotive trends other than the WSD will also influence the driver's future cockpit and tasks tremendously. The biggest changes will come along with autonomous driving. Once cars drive fully autonomous, the windshield and its see-through displays may lose importance or even be omitted. The algorithms are improving continuously but still require the driver to take over control in difficult situations. Until cars drive fully autonomously, the display may help the driver to understand such situations and resume the driving task quickly and safely. Furthermore, we assume that windshield displays can help the user building trust in autonomous driving. As this is an important topic, researchers explore different ways of increasing trust, for example, through computer vision-based and anthropomorphic HUD interfaces [63, 125]. We investigated the trustworthiness of an autopilot when its actions and understanding of the surroundings are made transparent through different 3D visualizations (see [P6]). We showed that a miniature world, as a referent to the real world situation, can increase trust even more than an anthropomorphic visualization.

Once cars drive fully autonomously and people trust their abilities, the need for a windshield display as we consider it in this thesis might be diminished or even resolved. However, it is questioned whether manual driving will be abolished completely or if it will remain, for example, in cheap and old cars or as a hobby – which would frame a future for the WSD.

AR Consumer Devices Simultaneously to the HUD, AR devices for the daily and permanent use are in development and expected to be the next generation consumer device, potentially replacing the smartphone. Once such a technology is available and people are used to wear it continuously, they will most likely keep wearing and using it in the car – which would make the WSD superfluous. However, for in-car use see-through HMDs would need to become extremely light-weight and unobtrusive and provide a larger FoV without blocking or influencing the driver's peripheral vision. Then, windshield displays will need to provide considerable benefits compared to such devices to assure itself a place in the future car. Yet, such AR devices will not be available any time soon as their development is just as challenging as the realization of a full-size 3D windshield display.

5.2 Expected Display Characteristics (Size & Depth)

Academia and industry work on extending the head-up display in size and depth. Reviewing the available HUDs, it seems that little size and depth advancements have been accomplished in the last years. Yet, car manufacturers and suppliers advertise with AR head-up displays and show off working prototypes at recent technology exhibitions such as the CES (Consumer Electronics Show). For example, Volkswagen presented an AR HUD with an image of $10° \times 4°$. Instead of a full depth coverage, they decided for two layers which will spatially separate the AR information from the screen-fixed content such as infotainment functions (in 2 m and 15 m). They further want to display content only on the drivers' demand and depending on the gaze, e.g., hiding irrelevant information to lower clutter [1, 49, 64]. Panasonic developed an integrable HUD which reaches a virtual image with $12° \times 5°$ and an image distance of 10 m [92]. Wayray presented a holographic AR HUD with gesture control and an image size of $11° \times 8°$. This HUD is also developed as an aftermarket version to upgrade existing cars with a reduced image size and distance ($8° \times 4°$, 10 m) [85, 36]. A lot of research and development is invested in aftermarket and motorcycle HUDs, such as the Visteon HUD and the Nuviz helmet which even won the innovation award at CES 2018. This underlines the need and the expected safety benefits.

These systems deliver a virtual image which is approximately four times as big as the one of current HUDs – but they are still far from covering the entire windshield. Yet, the various interface designs and concept cars show that most car manufacturers aim for a full-size 3D WSD, such as the one from BMW [11]. However, the realization of such a display is challenging and will surely take a couple of years. But the considerable investments promise that large 3D windshield displays will be available in the future. This indicates that the display size and depth coverage will grow gradually. Consequently, it justifies researching the change from the current head-up display to the future windshield display and specifically the exploration of user interfaces (e.g., the content, its placement and layout) as well as the application of prototypes with varying abilities.

5.3 Expected User Interface

The presented content, the implemented stabilization approaches, the used placement concepts and the interactivity of the WSD will depend on its technological realization and abilities. Although there is still a lot of research needed until the windshield displays are feasible and market-ready, the knowledge and experience we gained during the presented research and in regard of the trends and advancements described above lets us expect the following features and directions of development.

Content We expect that future windshield displays will present a larger amount and variety of content, particularly non-driving-related, personal content. To counteract phone use, smartphone content is already accessible through in-car (head-down) display and external HUD devices. Displaying this content on the HUD could further contribute to road safety. Accordingly, we expect that future windshield displays will host (more) non-driving-related and personal content from other in-car displays as well as the smartphone. This will come along with more freedom to personalize the WSD content. Nevertheless, future research has to ensure that the use of smartphone functions does not increase and drivers become overly engaged and distracted.

Information Stabilization AR is one of the major motivations to extend the HUD to a WSD. It is assumed to be safer and preferred compared to a classic screen-fixed display and so far research seems to overall confirm this hypothesis. Accordingly, we expect that AR will be launched with the first WSD version. Nevertheless, screen-fixed content will remain the standard for most WSD content, also for content that is associated with the surroundings but cannot be annotated to the real object as it is not visible to the driver. We do not expect that head- or gaze-stabilization will be realized in the car, unless AR glasses will be used to compensate for the unavailable WSD.

Information Placement We expect that the windshield display will spatially separate driving-related from unrelated content. We think that the layout will be similar to our revised view management concept but may feature less areas (like the VW showcase [1, 49, **?**]). We further think that drivers will not be allowed to place content as liked across the windshield and also highly doubt that the layout will be personalizable any time soon. Potentially, information will be superimposed only on the drivers' demand to lower distraction, load and temptation to engage into interacting with particularly personal content (see [P3]).

Interaction The current interaction concepts and controls will probably not be usable with a large, 3D WSD. The (AR) items may move around the scene and be located in different distances as they are registered to real world objects. Classic controls are designed for simple 2D interfaces and are limited to actions such as up/down or left/right. Such controls (for screen-fixed content) will need to be complemented with new interaction methods, such as gestures and finger pointing.

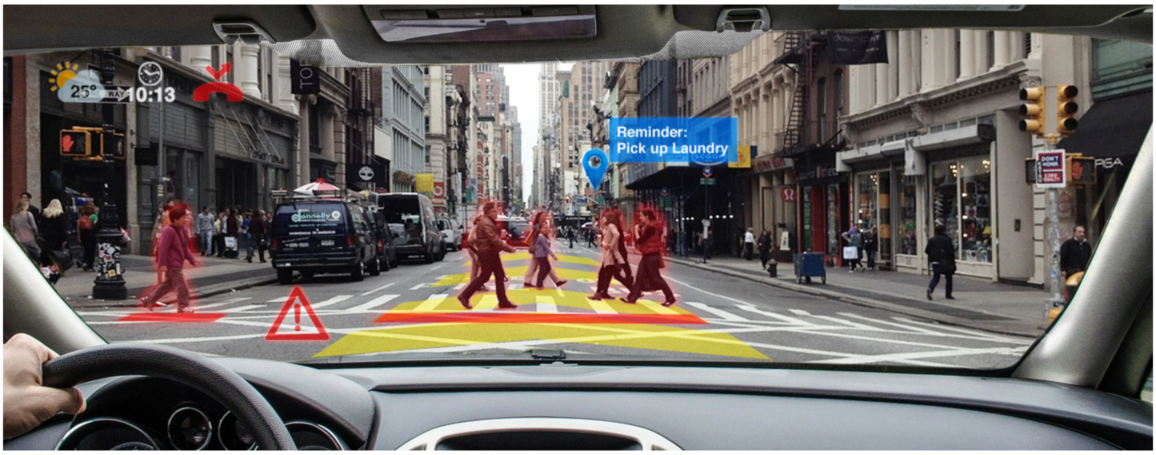

Figure 5.1: Mockup of how a future windshield display could look like. It combines registered and screen-fixed content and makes use of the entire windshield area as well as the depth. Image based on `https://pixabay.com/de/leben-schönheit-szene-stadt-864373`, retrieved on May 2, 2018.

6 CONCLUSIONS

Since major car manufacturers re-discovered the head-up display and successfully introduced it to the market, it is gaining increasing attention and acceptance. The head-up display is the safest one of the standard in-car displays and helps particularly in regard of visual perception and information uptake (see section on *Risks & Benefits*). Users value this support to such an extent that they stop accessing the provided information on other displays [117]. To exploit the HUD's benefits, substantial effort is invested into enlarging the image size and depth. Currently, the vision of a windshield display that spans a three-dimensional display space covering the driver's entire visual field through the windshield is technologically not yet realizable. However, gradual and steady advancements suggest that a windshield display will be available in the future.

The HUD's prominent position is its major advantage but also its biggest risk – as its proximity to the outside scene enhances information uptake but also invites the driver to attend the display's content instead of the driving task. This trade-off raises the question whether ***the extension from the head-up display to the windshield display is reasonable and desirable (lead RQ)***. We approached this question by assessing the risks and benefits of the new display space and depth coverage and particularly by investigating five research questions. We developed a design space and prototypes which fit the entire spectrum from the classic HUD to the envisioned WSD. We conducted applied, human-centred research in the areas of information content, perception, placement and stabilization. In table 6.1, we present our five research questions and provide a short answer based on our and related research.

As noted earlier, we regard the windshield display as reasonable and desirable when there is content which (A) is worth being presented to the drivers, (B) requires or profits from the extended display space and (C) potentially benefits from a separation in depth, or registration with the physical world.

(A) We learned from our research that the drivers' content preferences diverge strongly. Since superfluous content on the WSD increases the risk of distraction, we suggest to allow drivers to personalize their display's content. Most drivers give priority to driving-related content that supports them in executing their tasks. As such content can be time-critical and a 3D WSD can speed up information recognition, we regard the display of driving-related content as worthwhile. There seems to be a growing interest in having non-driving-related content displayed which we regard as desirable if it reduces the dangerous smartphone use. As we assume that such content is more distracting and hence poses a higher risk, future research will need to study its impacts on the driver and safety. ***We conclude*** that safety-relevant information and potentially also personal information is worth being presented on the windshield display.

(B) The HUD's display space is not sufficient to host a larger amount of content and to spatially separate the various types of content contextually, which helps finding information and is wanted by the drivers. Consequently, an extended display space is required. Within a display area of approximately 30° horizontally and 20° vertically centred around the drivers' line of sight, the information uptake and driving performance seem to be comparable with the HUD area, provided that the driving scene is fully perceptible. Permanently visible information should be placed within this visual field (30° × 20°). The remaining space is regarded as unsuitable for permanently visible information but needed for world-registered content. The (screen-fixed) information should be complemented with (temporary) world-registered information which makes use of the entire display area – if possible, the entire windshield. Augmented reality helps understanding both information and situation and can increase the drivers' focus on the driving task and should therefore be applied whenever the content is related to the outside scene. ***We conclude*** that it is meaningful to extend the display area to as large as possible.

(C) Augmented reality is the most pronounced argument in favor of the depth coverage. Related research suggests that AR requires accurate depth matching. Our research indicates that a 2D WSD might also do, however, from the current state of research we cannot determine whether the accurate depth registration induces a performance and hence a safety benefit.
People are used to arrange items in 2D display spaces and apply similar patterns when doing so on the WSD. Assigning a depth in a 3D space is rather new to them and seems unintuitive. Nevertheless, drivers consistently decided for one standard depth layer and chose to place few items considerably closer or further away. We expect that arranging content in depth will become as natural and helpful as in 2D spaces once people get used to 3D interfaces, which use depth in a meaningful way. ***We conclude*** that a separation in depth (e.g., several layers) as well as a registration in depth is helpful and wanted by the drivers and that one single layer will not be enough for the future windshield display. Further research is needed to understand how depth can be applied as a meaningful design factor for screen-fixed content (e.g., to structure it) and to exploit the benefits of augmented reality.

Provided its interface is responsibly designed and used, ***we conclude from our research that the extension from head-up display to windshield display is reasonable and desireable***. We further think that the windshield display can increase the safety and the users' satisfaction – even in comparison to the conventional HUD. Nevertheless, more research is needed to fully understand the interrelation between the windshield display and the driver's visual perception, cognition, behavior and performance. We therefore refer to the needs for future research which we mentioned in the previous sections.

Table 6.1: Summary of our research questions and findings.

	Research Questions & Answers
1	**Which content could be presented on the windshield display?** Overall, the WSD's extended display space allows to present a larger amount of information as well as new content, which require a large display space or 3D. Related as well as our own research showed that drivers can imagine a large variety of content for the windshield display (see [P7]). However, when imagining the content of their personal display, the preferences in regard of amount and type differ strongly. Table 4.2 (see section on *Information Content*) and [P1] summarize our findings as answer to *RQ 1*. Drivers consistently prioritized driving-related content but seem to have an increasing interest in seeing non-driving-related content, e.g., from their smartphone, on their WSD. To reduce superfluous content and driver distraction, the WSD content needs to become personalizable.
2	**What design opportunities do HUDs and WSDs provide?** The key differences between HUD and WSD are the extended display space and the potential depth coverage – and thereby the transition from 2D to 3D. Researchers agree that the most prominent design opportunity resulting from the transition from HUD to WSD is augmented reality. The extended size and depth create new or interrelate with existing design factors, which we summarized in our design space (see [P7] and figure 4.1 in the section on *Design Space*).
3	**Which windshield display locations support information uptake?** Our as well as related research showed that the driver's performance in responding to appearing stimuli is best at the locations 5° around but particularly to the right of the center. The drivers' response performance correlates with the eccentricity, meaning that the closer the location is to driver's line of sight the better it supports information uptake. Furthermore, the response performance declines in an elliptical shape, which means that locations at the horizon level support information uptake better than equally eccentric locations in the vertical line (see [P5] and the section on *Information Perception*).
4	**At which windshield display locations should content be placed?** In general, we suggest that content should be placed at locations that promote a fast information uptake (see RQ 3) but do not hinder the driving task, e.g., through occluding the driving scene. The areas below the driver's normal line of sight (overlaying asphalt) are most suitable, followed by locations above the line of sight (overlaying sky). Overall, information should be placed within an area of approximately 15°. Registered information (AR) needs to make use of the entire windshield space and its location has to adopt dynamically to not occlude the point of interest. We summarized such guidelines in a *view management* concept which suggests 3D information spaces. We also approached this question by asking drivers where they want information to be presented. The locations chosen by the drivers are not considered safe, as they could occlude the driving scene and do not promote information uptake as good as the suggested concept does. We conclude that drivers should not be allowed to choose the locations at which content is placed (from the entire windshield space). We learned from the drivers' preferences and performance and refined our location suggestions, as depicted in the figure 6.1 (see [P1, P8] and the section on *Information Layout* and *Appendix [B]*).
5	**Which placement strategies are suitable for the windshield display?** HUDs are just now setting out from 2D display spaces. *Screen-fixed* placement has been the default and will remain relevant in the future simply because most content has no relation to the outside world. Whenever possible, our as well as related research suggests that *world-fixed* placement is the better alternative (see [P9]). *Head-stabilization* encounters its limits when it comes to the system's and driver's field of view (see [P2]). At the moment we cannot imagine a scenario in which head-stabilization is the better choice than a screen- or world-fixed placement in combination with other channels, e.g., auditive or haptic feedback (see section on *Information Placement Strategies*).

List of Publications & Own Contribution

The research presented in this thesis was conducted at Ludwig-Maximilians-Universität München (LMU Munich), IAV GmbH and University of California, Santa Barbara (UCSB) between 2013 and 2017. Within this time I collaborated with other researchers and students. The majority of the experiments was part of Bachelor's and Master's Theses which I supervised throughout the entire process. I supplied the initial theses' topics and research ideas and contributed primarily to the concept development, the study design and the analysis. I supervised the study conduct and implementation and contributed in few studies. The two studies presented in the publication [P1] were carried out at UCSB and were not part of a student's thesis. I was in duty of the ideation, the concept and study design, implementation, study conduct and analysis and supported and supervised during theses phases by the local researchers.

My contribution to the research and its single phases is depicted below each publication. All of the publications were written primarily by myself and reviewed by the co-authors. The publications [P1, P2, P5-P9] are part of this thesis.

[P1] Renate Häuslschmid, Donghao Ren, Andreas Butz, Florian Alt, and Tobias Höllerer. Personalizing Content Presentation on large 3D Head-Up Displays. Submitted to *MIT PRESENCE Journal, Special Issue on Virtual and Augmented Reality for Autonomous Driving and Intelligent Vehicles*. Under review.

Own contribution: I contributed largely to the ideation, study design, implementation, analysis, and the publication writing.

[P2] Renate Häuslschmid, Benjamin Fritzsche, and Andreas Butz. 2018. Can a Helmet-mounted Display make Motorcycling Safer?. In *Proceedings of the 23nd International Conference on Intelligent User Interfaces* (IUI '18). ACM, New York, NY, USA, 10 pages. DOI: https://doi.org/10.1145/3172944.3172963

Own contribution: I contributed largely to the ideation, study design, analysis, and the publication writing. I contributed moderately to the concept.

[P3] Renate Häuslschmid, Christopher Klaus, and Andreas Butz. 2017. Presenting Information on the Driver's Demand on a Head-Up Display. In: Bernhaupt R., Dalvi G., Joshi A., K. Balkrishan D., O'Neill J., Winckler M. (eds) Human-Computer Interaction - INTERACT 2017. INTERACT 2017. Lecture Notes in Computer Science, vol 10514. Springer, Cham. 17 pages. DOI: https://doi.org/10.1007/978-3-319-67684-5_15

Own contribution: I contributed largely to the ideation, study design, analysis, and the publication writing. I contributed moderately to the concept.

[P4] Renate Häuslschmid, Bastian Pfleging, and Andreas Butz. 2017. The Influence of Non-driving-Related Activities on the Driver's Resources and Performance. In: *Meixner G., Müller C. (eds) Automotive User Interfaces. Human–Computer Interaction Series*. Springer, Cham. 33 pages. DOI: https://doi.org/10.1007/978-3-319-49448-7_8

Own contribution: I contributed largely to the ideation and the publication writing.

[P5] Renate Häuslschmid, Susanne Forster, Katharina Vierheilig, Daniel Buschek, and Andreas Butz. 2017. Recognition of Text and Shapes on a Large-Sized Head-Up Display. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (DIS '17). ACM, New York, NY, USA, 821-831. DOI: https://doi.org/10.1145/3064663.3064736

Own contribution: I contributed largely to the ideation, study design, analysis, and the publication writing.

[P6] Renate Häuslschmid, Max von Bülow, Bastian Pfleging, and Andreas Butz. 2017. Supporting Trust in Autonomous Driving. In *Proceedings of the 22nd International Conference on Intelligent User Interfaces* (IUI '17). ACM, New York, NY, USA, 319-329. DOI: https://doi.org/10.1145/3025171.3025198

Own contribution: I contributed largely to the ideation, study design, analysis, and the publication writing. I contributed moderately to the concept.

[P7] Renate Häuslschmid, Bastian Pfleging, and Florian Alt. 2016. A Design Space to Support the Development of Windshield Applications for the Car. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 5076-5091. DOI: https://doi.org/10.1145/2858036.2858336

Own contribution: I contributed largely to the ideation, the concept, analysis, and the publication writing. I contributed moderately to the study design.

[P8] Renate Häuslschmid, Yixin Shou, John O'Donovan, Gary Burnett, and Andreas Butz. 2016. First Steps towards a View Management Concept for Large-sized Head-up Displays with Continuous Depth. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '16). ACM, New York, NY, USA, 1-8. DOI: https://doi.org/10.1145/3003715.3005418

Own contribution: I contributed largely to the ideation, concept, study design, analysis, and the publication writing.

[P9] Renate Häuslschmid, Laura Schnurr, Julie Wagner, and Andreas Butz. 2015. Contact-analog Warnings on Windshield Displays promote Monitoring the Road Scene. In *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '15). ACM, New York, NY, USA, 64-71. DOI: http://dx.doi.org/10.1145/2799250.2799274

Own contribution: I contributed largely to the ideation, study design, analysis, and the publication writing. I contributed moderately to the concept.

[P10] Renate Häuslschmid, Sven Osterwald, Marcus Lang, and Andreas Butz. 2015. Augmenting the Driver's View with Peripheral Information on a Windshield Display. In Proceedings of the 20th International Conference on Intelligent User Interfaces (IUI '15). ACM, New York, NY, USA, 311-321. DOI: http://dx.doi.org/10.1145/2678025.2701393

Own contribution: I contributed largely to the study design, analysis, and the publication writing. I contributed moderately to the ideation, concept.

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Terms & Abbreviations

2D / 3D registered The AR content matches the location (2D) or also the depth (3D) of the augmented object.

accomodation When focusing on an object (closer than 10 m), the eyes accommodate to its distance so that the object is perceived sharply.

AlloSphere The AlloSphere is a near-to-spherical VR situation room with a diameter of 10 m and a bridge to walk through it.

augmented virtuality (AV) Real objects are placed in a virtual world. In the context of the thesis, a driving setup is placed in a VR situation room..

augmented reality (AR) The real world is overlaid by a digital readout. In the context of driving, the digital (WSD) information is merged seamlessly into the real world..

car-stabilized / screen-fixed The static placement of content within a specific area on the (windshield) display (car-stabilized).

combiner A transparent mirror into which the HUD image is reflected to be visible to the driver.

conformal AR The augmenting information is designed and placed naturalistically.

ConTRe task The *continuous tracking and reaction task* requires the driver to control the horizontal position of a cylinder to match the position of another autonomous cylinder. Further the driver has to react to random green and red light through breaking or accelerating.

detection-response task The participant has to detect, recognize and respond to stimuli that appear within the field of view (on the WSD). For example, the participant has to press a button if the appearing stimuli has the shape of a triangle.

driving-related tasks Summarizes primary and secondary tasks.

field of view (FoV) The area which is visually perceptible to the human (human visual field)..

head-stabilized The static placement of content at a fixed position within the person's field of view.

lane change task (LCT) The lane change task requires the participant to drive on a highway with three lanes and to change to a defined lane upon a periodic trigger.

line of sight The line between the point the driver focuses on and the eyes. The driver normally focuses on down the road and slightly below the horizon and with a slight shift to the right. In driving research, the line of sight is assumed to be static.

non-driving-related tasks See tertiary task.

oculomotor mechanics The eyes rotate and accommodate in distance when focusing on an object which is closer than 10 m.

primary task In the context of the task level, the primary task describes all tasks that required to safely control and manoeuvre the car; e.g. lateral or speed control. In the context of the study design, it refers to the task that is most important or requires the most resources from the the participant (usually driving).

registration The AR content is placed spatially close to the related object. The AR information remains spatially close to the related object and hence moves along when the car or the driver moves.

secondary task In the context of the task levels, the secondary task comprises all tasks that are related to driving but not crucial for it; e.g. windshield wipers. In the context of the study design, the secondary task is performed next to driving and related to the perception of or interaction with the in-car system.

stabilization The (WSD) content is displayed at a fixed position; e.g. stabilized to the head or car.

stimulus/-li We regard a stimulus as a (simple) graphical item displayed on the WSD (mostly related to the detection-response task).

task level The drivers' tasks can be subdivided into the three task levels primary, secondary, and tertiary task.

tasks All actions a driver performs within the car.

tertiary task All tasks which are not related to driving but performed meanwhile; e.g. music control.

vergence When focusing on an object (closer than 10 m), the eyes rotate (towards each other) so that both eyes focus on the same point.

view management A concept or set of rules that defines the placement of content in a dynamic scene.

virtual image The (reflected) image that is visible to the driver through the combiner.

world-registered The AR content is placed spatially close to the related real world object.

WSD (vs. HUD) The windshield display differentiates itself from the HUD through an extended size (at least 40% horizontally and vertically) and potentially depth (multiple layers to continuous depth coverage).

APPENDIX

APPENDIX A

Prototype Variants and Test Environment

Below, the HUD and WSD prototype variants which were introduced earlier (see section on *Prototypes*) are explained in more detail. The basic construction principles as well as examples from literature and our own work are described.

Graphic Windshield Display Both, WSD image and driving scene are presented on one large display. Such setup is easy to realize and hence a common approach particularly to explore new concepts (e.g., [127]). Yet, as the HUD and scene are not spatially separated and unrealistic in size and distance, these setups are inappropriate for studies about visual perception.

We applied this setup in one user study that explored interaction with the WSD (see (3) in figure 4.2). Compliant with Gish and Staplin's [42] requirement, we did not apply such setup to evaluate the driver's perception.

Projected Windshield Display The superimposition of the image directly on the windshield is reached either through integrating transparent displays such as OLEDs into the windshield [13] or through the targeting of a (laser) projection onto the windshield [32, 136]. Both approaches are not investigated deeply, presumably, due to their disadvantages.

We implemented a projector-based WSD to explore its applicability for prototyping and its advantages and disadvantages in comparison with the conventional HUD approach [P10]. We placed a conventional, full-color projector in the co-driver's feet area and targeted it onto a mirror which forwarded the image to the windshield. The obtained image was of high quality and covered nearly the entire windshield (see (6) in figure 4.2).

However, in a car mockup the image is slanted like the windshield and focusing on it is demanding, particularly in the upper part (due to low image distance). As follows, we consider the display directly on the windshield as non-advisable. Yet, such realization might be an interesting and low-cost alternative particularly for trucks, busses and utility vehicles. Those vehicles often feature an upright windshield which renders the reflection in the windshield impossible, as also pointed out by Dingus et al. [31].

Mirrored Windshield Display As explained earlier, conventional HUDs are based on the principle of light reflection. A display is positioned below the windshield or a separate combiner that reflects the light and creates a virtual image that seems to float above the car's hood. HUD prototypes are often based on this approach, however, they are of varying fidelity and relevance for research on windshield displays. We regard 2D and 3D prototypes of medium to large size as relevant (e.g., [4, 17, 74, 111]).

We utilized a similar 2D setup of varying dimensions in five user studies. The setups shared the virtual image distance of approximately 1.7 m and were perceptible from any position (no experiencable eyebox). For the studies presented in [P5, P10] we lined up three 32" displays below the windshield and reached a virtual image of approximately $43° \times 24°$ (see (2) and (7) in figure 4.2). This setup was qualitatively and quantitatively compared to a projected WSD [P10]. Equivalently, we lined up two 32" displays and obtained a virtual image of approximately $51° \times 13°$ [P9]. When lining up several displays the image is subdivided through the displays' frames which might become problematic, for example, when testing augmented reality.

We also implemented a smaller HUD variant which can be used in conjunction with a real car. We placed a similar setup utilizing a 12" tablet and an additional combiner on its hood and obtained a virtual image size of approximately $8^\circ \times 6^\circ$ (see (1) in figure 4.2 and [P6]). Such setup could also host a larger display and further extend the virtual image distance, similar to the prototype from Liu [74].

Reflection-based setups are easy to implement and low-cost. In contrast to the projector-based variant, the virtual image is upright and presented in a larger distance which is easier to focus on. Distances of 1 to 1.7 m are easy to realize and similar to the ones of conventional HUDs (see paragraph on *Image Distance*). For larger distances, the image source and combiner need to be placed between car (mockup) and driving scene (see Liu [74] and [P6]). Prototypes with an image distance between 0.7 and 1 m require less space and could also be used in real-world studies, similar to the HUD smartphone applications (see section on *Technological Realization*).

When implementing such prototype, one has to compromize between image size and distance (as the image covers a smaller FoV when displayed in a greater distance, unless lenses are integrated). Furthermore, utilizing a standard glass pane as combiner will lead to two slightly misaligned images (*double image*) which can hamper the readability. The visibility of this effect can be reduced but not abolished through thin combiners.

See-through Head-mounted Display See-through HMDs still face technological challenges, which is why we currently consider them as inappropriate for the use in cars. As HMDs are head-stabilized by default, the conventional (screen-)fixed placement of the HUD content requires tedious implementation. The provided image size and resolution are often low and the construction often blocks the peripheral vision, which is highly important for driving [23]. Lauber et al. [68] tested the use of see-through HMDs in the car and described further problems.

Yet, we think that see-through head-mounted display prototypes might provide a good display alternative to motorcyclists. This application area faces tight space and weight restrictions and so it is not surprising that the count of available devices is still limited although a lot of effort is invested into the development (e.g., [30, 88], as discussed in [P2]). The display image can be monocular or binocular as well as 2D or 3D but is in any case separated from the driving scene. Accordingly, it is presented to one or both eyes and generated by means of a projection unit or a HUD-like construction which is attached to the helmet.

We based our helmet-mounted prototype on the principle of image reflection, which is typically applied for HUDs. We used a smartphone as display unit and amplified the setup with mirrors, lenses and a combiner to reach a small and light-weight prototype [P2]. The generated image covers a large field of view of up to $37^\circ \times 37^\circ$ and provides a perceived image distance of 1 to 2 m (see (5) in figure 4.2). To test this prototype, we used a motorcycle variant of our car mockup.

Monocular HMDs bring along the rivalry phenomena which leads to a blending of the images perceived through both eyes (augmenting stimuli are suppressed as they are conflicting with the image perceived through the other eye) [29]. To counter this effect, we advanced our setup to a binocular (3D) helmet-mounted display through shifting the setup to the forehead, however, this prototype has not been applied in an user study or published yet. Since only recently, toolkits for binocular AR glasses such as the Holokit and the Aryzon DIY kit are available and constructed equivalently.

Non-see-through Head-mounted Display Non-see-through head-mounted displays (VR glasses) slowly find their way into automotive UI research, however, they are rather applied for research on autonomous driving than HUDs (e.g., [7]). VR glasses are thought of being inappropriate technology for prototyping HUDs and WSDs as the WSD image and the driving scene are displayed through the same technology (like the graphic WSD). Furthermore, they have a near focus distance of approximately 2 m, a low resolution and hence a limited realism. As the driver is cut off from the surroundings, a virtual representation of a car mockup would be needed and matched perfectly with the real test environment.

We used the Google Cardboard in one formative study to display examples of full-size and 3D windshield displays to the participants [P8]. We also utilized the Google Cardboard in a performance test, however, this work remains unpublished due to lack of validity.

VR glasses and graphic and projected WSDs alike provide a low focus distance but a great opportunity for early-stage prototyping of WSD interfaces. Example scenes are fast and easy to implement as well as to adapt to the participants feedback. However the suitability of VR glasses for studies about oculomotor mechanisms is limited as they enforce vergence and accommodation conflicts which hamper performance and result in visual fatigue [48].

Augmented Virtuality Simulations In contrast to VR glasses, AV simulations are often 3D wall-projections that cover the entire FoV or even surround the user as in situation rooms. Such simulation rooms present a 3D virtual world and enable sound depth perception along with the unrestricted perception of the self and the car mockup. AV simulators such as the CAVE are expensive and complex and hence are rarely applied for driving simulations (e.g., [56, 72]). We used the AlloSphere, a near-to-spherical situation room, for our research about 3D information layouts [P1]. Both a real driving scene and the augmenting WSD content were displayed through the projection unit and framed through a car mockup to obtain an immersive experience (see (4) in figure 4.2).

Compared to VR glasses, AV simulations (can) feature a higher focal distance but drivers also suffer from the vergence and accommodation conflict. Such virtual worlds are highly complex to develop but can enable a realistic experience of the look and feel of a full-size 3D windshield display.

Test Environment For the driving simulator studies, we created car mockups which framed the windshield display to reach a more realistic setting (see figure 4.2 for examples). Real or artificial windshields and seats together with a gaming steering wheel and pedals formed the driver's workplace. In contrast to other automotive user interface research, realistic sizes of the windshield and the simulator scene were of particular importance to obtain a realistic visual field and sight but also to explore information placement across the windshield. Equivalently, we developed a motorcycle mockup with a real seat and a gaming steering bar.

When examining non-immersive (VR) prototypes, we adjusted the test environment to ensure a proper perception of the WSD image. We cut off ambient light and adapted the brightness of the simulator scene to be comfortable also in long-lasting driving tasks. This furthermore increased the relative brightness of the WSD image.

Ambient lighting situations vary considerably already during simple day- and nighttime shifts. We value the unimpeded perception of the examined system as more important than a bright daylight scene. Once the abilities of the future windshield display are known, the drivers' perception of the WSD image has to be researched under diverse natural lighting situations.

Appendix B

Revised View Management Concept

The first version of the view management concept is introduced in [P8]. We learned from our studies that the view management concept led to a better response performance than the personal layouts [P1]. Highly important information was perceived faster than less important content, which is highly desirable. Overall, we think that the results support the concept. However, as the first version of the view management concept was based primarily on literature about response time measurements, we now aim to balance it against the users' preferences. Accordingly, we adjust some areas of the view management concept to provide an even more consistent layout that also follows the users' preferences (see figure 6.1).

Many participants lined up icons along the bottom edge of the windshield. This lineup is similar to the vehicular and personal areas proposed in the view management concept. This suggests to adjust these areas to be of the same height and start at the same vertical position to create a more connected layout with more space available. Larger areas would allow a larger presentation of the icons, which could promote faster reading of especially complex information, such as maps or text, but might also increase distraction. In addition to the bottom edge, some drivers placed information on the left edge of the windshield. We do not follow this idea since this area is highly important particularly for cross traffic and left turns. Furthermore, our participants grouped items with the same context which supports our notion of assigning information to context-based spaces. Further observations are reported in the publication [P1]. We did not identify any generally consistent patterns regarding locations or depth values from the user-proposed layouts. This suggests that there is no generally intuitive position in the windshield area or in depth for the different types of information.

To optimize the view management concept, we suggest the following changes: We propose to move the area for personal content (3) upwards to $-5°$ so that the content is at the same vertical position as the driving-related content. The areas remain separated horizontally for a better layout structure. The personal area (3) should be adapted to the HUD area (5) in depth. We further suggest to merge the text area (2) into the HUD area (5) since we found similar results for the two tested areas and the text to the

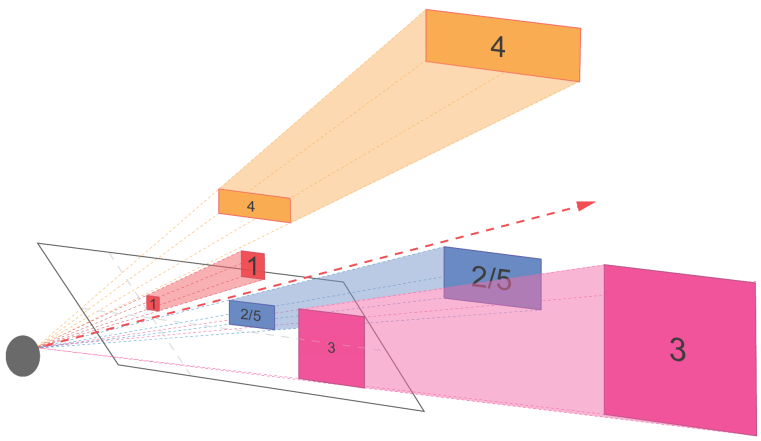

Figure 6.1: The revised view management concept: (1) urgent warnings, (2/5) driving-related information and prose texts on demand, (3) personal and (4) ambient information. The area for environment-related information (augmented reality content) is not depicted in the figure.

right of the center could occlude important parts of the driving scene. Consequently, a space sharing strategy will need to be found, e.g., hiding the driving-related content when a text is to be displayed (text should not be displayed on a regular basis) or extending the HUD area downwards and re-aligning the content. The areas for urgent warnings (1), ambient information (4) and environmental information (not depicted in figure 6.1) remain unchanged from the first version of the concept. Depending on the amount of the displayed information, the area for ambient information (4) could be merged into the area for personal information (3).

Regarding the depth ranges (zones), we suggest to adjust the depth range of the personal area (3) as well as the ambient area (4) to match the zone of the HUD area (5). This allows the driver to switch within the areas without additional eye accommodation effort. The zone for urgent warnings remains as suggested since our participants and the experimenters experienced a stimulus appearing in this area as interrupting and acquiring immediate attention. This supports the notion to use this area exclusively for very urgent and safety-relevant warnings. The zone of environmental information remains as suggested.

Eventually, the view management will need to be adapted to the driver. The areas for vehicular and textual information (2/5) as well as for urgent warnings (1) are placed rather centrally in the windshield and should in general be well perceptible for all drivers. However, the exact positions depend on the driver's height and seating position, so that the display should be calibrated to ensure that these areas won't shift up- or downwards and be invisible or hide the road scene. Furthermore, the areas for personal (3) and ambient (4) information are aligned to the top and bottom edge of the windshield and, consequently, need to be calibrated to the driver to ensure their visibility.