A Design Space to Support the Development of Windshield Applications for the Car

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ABSTRACT
In this paper we present a design space for interactive windshield displays in vehicles and discuss how this design space can support designers in creating windshield applications for drivers, passengers, and pedestrians. Our work is motivated by numerous examples in other HCI-related areas where seminal design space papers served as a valuable basis to evolve the respective field – most notably mobile devices, automotive user interfaces, and interactive public displays. The presented design space is based on a comprehensive literature review. Furthermore we present a classification of 211 windshield applications, derived from a survey of research projects and commercial products as well as from focus groups. We showcase the utility of our work for designers of windshield applications through two scenarios. Overall, our design space can help building applications for diverse use cases. This includes apps inside and outside the car as well as applications for specific domains such as fire fighters, police, ambulance.

Author Keywords
Windshield display; head-up display; in-vehicle interfaces; automotive interfaces; design space

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
Today, drivers perform many activities while driving. This goes far beyond just maneuvering the vehicle, which is still the primary driving task. Besides, drivers want to adjust comfort features such as tuning the air conditioning, accessing entertainment features (e.g., radio, music player), communicating (phone calls, text messages), and retrieving information (e.g., navigation, vehicle information) [11, 76].

For many of these activities, the driver needs to receive visual feedback or information. A multitude of displays has been established in the car to provide visual output. Traditionally,

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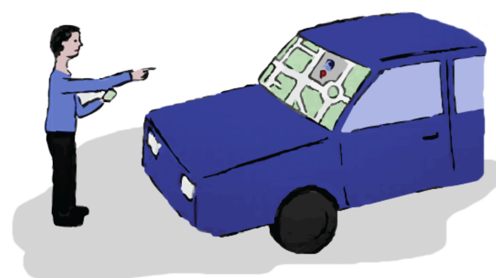

Figure 1. Windshield displays enable novel applications – not only for drivers but also for people outside the vehicle. One example is a navigation system that can be used by pedestrians passing by. We chart the design space for such applications and show how designers could benefit when creating novel WSD applications.

such information is displayed in the instrument cluster or on the center stack (central information display, CID). More recently, head-up displays (HUDs) find their ways into cars. Their advantage is that they are close to the drivers' focus point as they observe the road. Hence, information can be quickly accessed while still being able to keep track of the road.

Windshield displays (WSDs) extend the display real estate[1]. This is not only helpful for meeting the ever-increasing demand for new functions for drivers – provided by the car itself or through external apps – but such displays create novel opportunities also for applications that can be seen and interacted with from the outside of the car, both while parking and while driving. In the near future these needs may become even more pronounced with highly-automated and autonomous driving, allowing the user to engage in new driving and non-driving-related tasks [75]. WSDs may come in handy, particularly in situations where drivers need to take over control, since their view is already directed towards the windshield.

While research is starting to take up on such displays, the focus of in-car functions now changes from safety and navigation (as will be shown later) to discover more entertainment functions – in particular social interaction. To bridge that gap, we suggest

[1] In the remainder of this work we refer to windshield displays (WSDs) as any type of display using (parts of) the vehicle's windshield – independent of where it is visible from (inside/outside) and by whom (driver, passenger, or passerby) – as opposed to head-up displays (HUD) that are only visible from the driver inside the car and show information close to the usual viewpoint.

a categorization for windshield display apps as well as a design space meant to support the creation and design of future apps.

We combine findings from reviews of research projects, papers, patents, and commercial products with a series of focus groups to present a categorization of windshield display applications. Furthermore, we explore core dimensions of a design space for WSDs – including display technology, interaction, visualization, context, and user. This is meant to support the designer's creativity for the development of novel ideas as well as design decisions towards the implementation of certain systems. Based on sample applications taken from these categories, we demonstrate the usability of the design space by discussing two thought experiments on exemplary applications.

CONTRIBUTION STATEMENT

We present a categorization of specific WSD applications that were derived from a literature review and focus groups. Furthermore, we contribute a design space for WSD applications for use inside and outside of vehicles. Our research is complemented by showcasing how designers are supported by the design space, when it comes to creating WSD applications.

BACKGROUND AND RELATED WORK

During the design and development of in-car applications and in-vehicle information systems (IVIS) the involved parties are urged to consider a comprehensive set of guidelines, rules, laws, and standards [4]. Many of them intend to facilitate the interaction with the IVIS, limit the driver's distraction from the primary driving task [21], and thus ensure safe driving. They contain recommendations and enforcements regarding interaction design and support the design process, e.g., by providing hints regarding location and installation of displays and controls, font sizes, or feedback about the system status.

While guidelines and standards provide beneficial hints to avoid creating distracting interfaces, they often do not support the designer when exploring different design options for a specific context. The importance of exploring design spaces has been emphasized in the human-computer interaction (HCI) community: Describing and analyzing design spaces helps to understand differences between designs but also to find and propose new opportunities [24]. Early work concentrated on basic HCI aspects, such as a classification and taxonomy of input devices [22, 25]. Similarly, design spaces have also been proposed for InfoVis [24, 29] and for various subfields of HCI. In particular, the latter ones are a valuable basis for the development of the corresponding field. For example, Ballagas et al. [12] explore the design space for mobile phone input. Mueller et al. explore public displays [67], and Nigay et al. did so for multimodal interaction [72]. Also, automotive user interfaces are subject to design space explorations. Kern and Schmidt [55] present a general design space for driver-based automotive UIs. Their goal is to provide a tool that comprehensively describes, analyzes, compares, and discusses different UI arrangements (car-related input / output devices). Also, it can be used to identify new interaction opportunities and placements for controls.

For automotive augmented reality, Ng-Thow-Hing et al. [70] present a user-centered process and principles for creating and evaluating designs for AR displays. Most closely related to our research is the work of Tönnis et al. who provide an early design space for augmented reality (AR) apps for HUDs [98]. In contrast, our work considers a comprehensive set of design-relevant dimensions for WSDs in general, such as technology, interaction, content, and user. In this way we cover the entire process of developing windshield display applications rather than focussing exclusively on information presentation.

WINDSHIELD DISPLAY APPLICATIONS

At the outset of our research we collected a set of possible applications and use cases for windshield displays through a comprehensive literature review and focus groups. This resulting set helped us to understand the variety of applications and served as a basis for the design space presented later.

Methodology

Literature and Patents Review

We performed an extensive literature and patents review (> 125 papers and patents) on applications based on the terms *windshield display*, *head-up display/HUD*, and also *car side and rear windows* (to find related issues), based on the information retrieval process proposed by Galvan [41]. We used those general terms in order not to exclude early approaches or proposals by simply searching for too specific terms. We searched through search engines, such as Google Scholar, ResearchGate, ACM Digital Library, IEEE Xplore. Furthermore, we iteratively went through all citing and cited references of both papers and patents. We then selected the ones related to use cases for the aforementioned displays and windows.

From the literature we then identified use cases, ideas, prototypes, and applications and collected them in an Excel file. We documented name and description of the idea, graphics (if available), used window/display, and development status (idea, simulation, prototype, market launch) as well as reference type (literature or patent), author(s), and year. We documented each use case. If we found a use cases several times we documented it with a cross-reference, only counting it once.

Focus Groups

We complemented our collection by conducting three focus groups. The focus groups concentrated on the desires of current but also future users, particularly in the entertainment and communication area. We recruited students with valid driver's licenses for all focus groups. One focus group was conducted with participants familiar with the topic of WSDs and existing literature; the remaining participants were unfamiliar with WSDs and came from different fields. Altogether, 14 students took part (six female) with 4 to 6 participants per focus group. The participants were aged 21 to 26 with a mean age of 24.

To conduct the focus groups, we derived rules and best practices for focus groups and collected them in the form of guidelines for the semi-structured sessions [61, 99]. Furthermore, we prepared a discussion outline and nine questions to encourage and guide the exploration phase. Those questions varied slightly to cover different aspects and reduce the number of redundant use cases. The overall procedure was the same for all groups. After the introduction, three initiation questions were

Category		
Subcategory	**Description**	**Examples**
Safety		
Vision Extension	extension of the driver's view by displaying occluded objects	wall-see through [103], transparent pillars (FG)
Vision Enhancement	enhancement of the driver's vision in bad viewing or lighting conditions	night and pedestrian vision [85], automatic sun shade (FG)
View Point	display of the views of virtual or real cameras; often replacing mirrors	virtual rear mirror [66], virtual side mirror (FG)
Spatial Awareness	improvement of the driver's understanding of the space around the car	safety grid showing the distance to vehicles [90], marshaller (FG)
Monitoring Surroundings	safety-relevant information about the environment	crash warning [58], approaching police (FG)
Driver Monitoring	driver performance and physical state observation	driver drowsiness alert [94] (FG)
Lane Change & Intersection	support in turning or changing lanes safely	overtaking assistant [38], driving on the right lane requirement (FG)
Breakdown	they help the driver in breakdown situations	warning triangle [86] (FG)
Specific Support Systems	systems directed at a specific party, support several tasks, or provide various information	racing car assistance [65], elderly visualization with integrated visual acuity (FG)
Vehicle Monitoring		
Vehicle Status	information about vehicle parts and the momentary status of the engine	monitoring of specialized vehicles [17], dashboard (FG)
Supervision	support in supervising the vision of the vehicle's sensors; most of they aim to increase trust	autonomous driving and ACC detection display [16]
Fuel & Battery	information about the current fuel or battery status	battery reach [31], charging status (FG)
Navigation & geo IS		
Path Finding	support in finding the way to the target	3D arrows [96], navigation with map and registered hints (FG)
Car-Following	support when following a car	projected virtual car [69], car mark up (FG)
Traffic & Street Signs	display of traffic signs currently applying; street signs and names	speed compliance warning [28], green traffic light continue (FG)
Points of Interest	additional on-route information to find people, shops or services	roadside objects [40], mountaintop peak display (FG)
Public Transport	support for commuters who switch to public transportation	BusMobile with schedules and park&rail and waiting passenger information (FG)
Entertainment & Communication		
Commercials	commercials for products or services, e.g. restaurants or promotions of stores	Taximedia, an advertising system for cab fares [8], drive-through menu ordering (FG)
Economy & Costs	economical driving and costs display	economical recommender system [53] (FG)
Work & Tasks	information about general tasks or activities or (office) work tasks	location-based reminders [64], activity suggestion generator (FG)
Driver Mood & Status	observation of the driver's status to promote a specific mood or physical state	Breakaway, a break recommender system [51], cheering-up display for construction zones (FG)
Education	the driver can gain knowledge or learn a specific behavior	CarCoach; feedback on driving performance [89], language learner application (FG)
Gaming	game play alone or together with others	car racing [100] or name or city guessing (FG)
Multimedia & Web	general information; music or video player; access to the Internet or news; specific for passenger entertainment and waiting times	passenger entertainment and information system [63], karaoke (FG)
Arts & Photography	picture or arts presentation, applications which enable drawing and taking photos	a road scene illustrator [95], photo app with slide shows and an outside targeting camera (FG)
Atmosphere	creation of a different atmosphere in the car by displaying different surroundings or ambient lights	candlelight [17], sleepover atmosphere (FG)
Public Display	public information to the outside	an outside projection of the parking ticket [17], passers-by navigation (FG)
Observation	observation of a person, normally relatives, or an object and its state	CareNet to observe elderly relatives [30], self-mirror (FG)
Social Interaction	social interaction with other parties than drivers	video conferencing on Skype (FG)
Driver 2 Driver Communication	communication with other drivers	Last Gentlement (rewards) [59], single driver marking (FG)
Internet of Things	access to or control of things	smart home (FG)

Table 1. This tables explains our classification of windshield display applications into five main categories and several subcategories. Also, it provides two examplary applications for each subcategory, one from literature and one identified in the focus groups (marked with "FG")

asked to encourage discussion: *What do you do while driving? What would you like to do? What situations are strongly annoying for you?*

After the initiation phase, the moderator led over to the exploration phase: *If there were no technological or safety constraints, what information would you personally like to be conveyed to you during driving?* When the count of created ideas bottomed out, the moderator further encouraged the discussion by asking how a WSD could support them in one of the three scenarios: *While commuting, on a long highway journey, and during a vacation in an unfamiliar city*. Next, more specific trends and topics were introduced to the discussion: *information about other vehicles, the surroundings, the own (electric) car, support for elderly people, or being on-line*. In addition, one of the following applications was explained: (1) *social status sticker* (driver share short status texts which are visible as stickers on the WSDs of other drivers [83]), (2) *entertainment channel* (information such as emails are accessible during waiting times at traffic lights on the WSD [6]), or (3) *roadside objects* (information about the environment can be accessed by means of the WSD [40]). Lastly, the moderator asked for ideas or statements not mentioned so far.

Each focus group lasted for roughly one hour. The sessions were audio recorded to ensure the moderator can focus on leading the group and to document ideas comprehensively and correctly. All participants gave permission in the beginning.

Finally, we collected all mentioned use cases including name, description, and utilized window/display in a spreadsheet. Use cases that came up several times were documented only once.

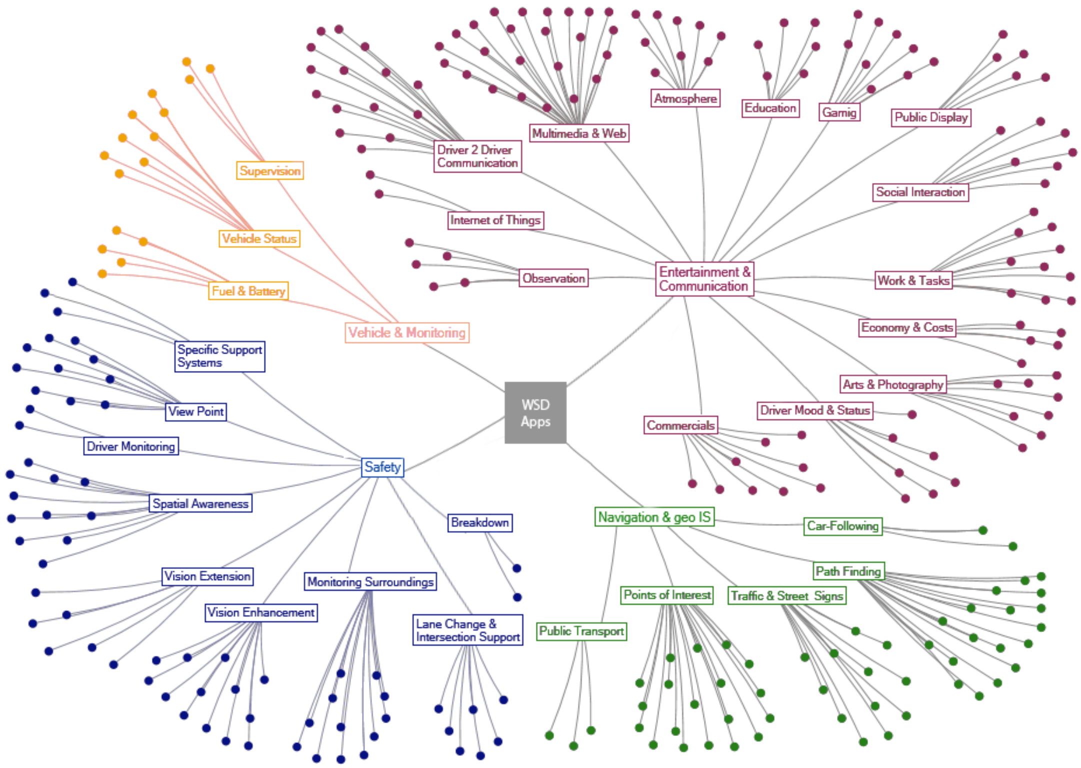

Figure 2. Overview of collected use cases: Safety (blue), Vehicle & Monitoring (yellow), Entertainment & Communication (magenta), Navigation (green).

Results

We collected 96 different ideas; 71 ideas were found in literature and 25 ideas from patents. 31 % of the ideas are *safety*-related, 43 % belong to *entertainment and communication*, 4 % of the ideas support the driver in *monitoring* the *vehicle*, and 22 % in *navigational tasks*. From the focus groups we collected 115 new ideas. Use cases are distributed as follows: 14 % *safety*, 3 % *vehicle monitoring*, 11 % *navigation & geo IS*, 47 % *entertainment & communication*. We also derived 28 use cases for special vehicles (police/ambulance) (24 %).

As a next step, we ordered all ideas by allocating them to predefined first-level categories. We based these first-level categories on the ones proposed by Brandt [19] with slight modifications, so as to reflect the application areas of WSDs:

Entertainment & communication. Information systems which enable communication and are entertaining.

Vehicle monitoring. Information about the vehicle itself.

Navigation & geo information systems (IS). information about the trip or path.

Safety. Information about the surroundings with the purpose to increase driving safety.

We subdivided the first-level categories (Table 1), adapting and extending the classification presented by Schroeter at al. [84]. The table presents all subcategories and provides a short description for each subcategory. It also lists one application derived from literature and one suggested in a focus group, respectively. Figure 3 provides an overview of the different categories and the distribution of all ideas among the categories.

DESIGN SPACE

Based on the list of applications we derived a design space for windshield display applications. For the design space, we did not only consider literature on use cases for windshield displays but also on WSD presentation, interaction with WSDs, and technological approaches to realize such displays. Furthermore, we reviewed existing design spaces, guidelines, surveys, and classifications related to HUDs, general in-vehicle displays, in-car interaction, and (AR) information presentation. We merged proposed classification and categorization approaches suitable for windshield displays. Moreover, we added categories and dimensions to our collection based on well-known (or novel) approaches or proposals in application and technology papers. Doing so, we focused also on characteristics of WSD currently popular in research: large size and 3D-registered images. Furthermore, the potential observers and persons possibly interacting received particular attention: A large-sized display could superimpose its image also to other parties than the driver, inside and outside of the car. Finally, we ordered and grouped all aforementioned aspects into dimensions and categories to complete the design space.

We defined five dimensions for our design space: (1) *User*, (2) *Context*, (3) *Visualization*, (4) *Interaction*, and (5) *Technology*. Each dimension consists of two to five categories. All categories, dimensions and characters are listed with a short description and an example reference in the following.

User

Currently, WSDs are usually targeted at a single person – the driver – with regard to interaction and observation. However, with increasing projection space, future systems may also

Dimension	Category					
User	User Mode*	Single User	Multi User			
User	Observer	Driver	Co-Driver / Passengers	Road Users / Passers-by		
User	Actor(*)	Driver	Co-Driver / Passengers	Road Users & Passers-by	Nobody	
Context	Application Purpose	Safety	Navigation & geo IS	Vehicle Monitoring	Entertainment	
Context	Information Context	Environment	Vehicle	Person	Time	
Context	Driving Mode*	Driving	Waiting	Parking		
Context	Level of Automation	Manual	Semi-automated	Autonomous		
Context	Privacy*	Public	Personal	Private		
Visualization	Level of Augmentation	Reality & loose Information	Augmeted Reality	Virtual Reality		
Visualization	Registration*	Unregistered	2D registered	3D registered	Gaze-dependent	
Visualization	Field of View Position	Foveal	Central	Peripheral / Ambient		
Visualization	Presentation	Symbolic	Naturalistic			
Visualization	Graphic Design Factors	Color	Transparency	Size	Motion	
Inter-action	Input Modality	Touch & Controls	Gestures	Gaze	Speech	Behaviour
Inter-action	Multimodal Feedback	Visual	Haptic/Tactile	Audtiory	Olfactory	
Technology	Image Generation	Image reflected on windshield	Image on windshield			
Technology	Size*	HUD (rather small)	WSD (rather large)			
Technology	Depth*	Single-layer (2D)	Multi-layer	Continuous (3D)		
Technology	Display Factors	Color depth	Transparency	Brightness	Resolution	

Figure 3. The design space we propose consists of four core dimensions – content, visualization, interaction, and technology (*exclusive selection).

allow the presentation of content to other passengers in the car, or – with outside projections – by other road users. Thus, we distinguish three different aspects in this dimension.

User Mode
While many common WSDs (such as a head-up display) can be used exclusively by the driver (*single user*), larger WSDs could enable *multi-user* interaction (e.g., for other passengers, people in other cars, or on the sidewalk). Application areas are game play or car-to car-communication.

Observer
This category describes the WSD observers. Depending on the selected technology, the image may be visible to the *driver* only, to the *co-driver or passengers*, or to *other road users including passers-by* on the side walk. The classic HUD is only visible to the driver when his eyes are within the eye-box – a predefined 3D space depending on the HUD position. Using other approaches to generate the image on the windshield could also make it visible to other occupants and to other road users or passersby, for example for ads [5, 86].

Actor
If the display is visible to a particular person, this does not necessarily mean that this person can also control the display. Hence, we distinguish between *observer* and *actor*. As actors we consider the *driver* as a main user, the *co-driver & passengers* as alternative actors inside the car, and other *road users & passersby* as potential actors outside of the car. Furthermore, there may be apps exclusively controlled by the system itself (for example, crash warnings), making the system the actor.

Context
Depending on the current context, WSD applications might provide different features and options or behave differently. This relates, for instance, to the purpose of the application, context information of the environment, whether the car is moving or not and the current level of automated driving.

Application Purpose
This category is directly based on our application classification. We distinguish between *safety*, *geo IS & navigation*, *vehicle monitoring*, and *entertainment & communication* applications.

Information Context
The information context may be relevant for placement and visualization (for example, dynamics). Based on two context collections from related work [82, 92], we came up with the following information contexts: *environment* (e.g. weather, GPS position) [82, 92], *vehicle* (e.g. tire pressure, temperature) [82], *person* (e.g. blood pressure, SMS) [82, 92], and *time* (e.g. current time, countdown) [92].

Driving Mode
The driving mode represents the current status of the vehicle. Selker, Burleson and Arroyo [88] differentiate between driving and non-driving condition and propose separate applications for each condition. This is important to differentiate in order to consider the driver's tasks, and therefore mental and physical workload, when the application is used. In our design space, we differentiate three modes: In the *driving* mode, the vehicle is moving. The *waiting* mode is limited to the waiting time when the car is stopped (e.g., at traffic lights). It is in a way comparable to semi-automated driving since the driver is free

to perform additional tasks but still has to monitor the surroundings. A car is *parking* when standing in a parking lot with engine off and no person inside.

Level of Automation

Automated driving can be divided into five support levels [3, 50]: no-automation (level 0), function-specific automation (1), combined function automation (2), limited self-driving automation (3), full self-driving automation (4).

Windshield displays and autonomous driving are technologies that fit well together: autonomous driving and new driver assistance systems give the user spare time while sitting in the car: they perform more non-driving related tasks [34]. In automation levels 1 to 3, the driver needs to monitor the vehicle or take over control. Hence, the car interior cannot completely be modified for autonomous driving. On the other hand, current cockpits need new concepts to enable new interaction possibilities when less attention to the road is required. The windshield display suits both, the driver-controlled and autonomously controlled vehicles, and can be the perfect match for the transformation: It can support the driver in controlling the vehicle and in performing completely unrelated non-driving-related tasks, but most importantly, it allows for easy task switches.

For the design of WSD applications it is very important to know which driving-related tasks the user has to perform. The level of automation gives insights in how much the driver has to be involved in driving, mentally and physically. Furthermore, it is important to also consider the driver's supervision task and the moment of the take-over-request when the control is handed back to the driver. These tasks are very demanding and safety-critical [44, 78] and are important for the design.

In our windshield display design space, we differentiate the following levels of driving automation: *manual*, corresponding to level 0 automation, *semi-automated* (level 1 to level 3), and *autonomous*, corresponding to level 4 automation. When designing an application for semi-automated driving, the level of automation has to be considered in more detail, but also the automated control units, as mentioned earlier. As there are more variables than only the level of control, we summed up the levels 1 to 3 to *semi-automated driving*.

Privacy

Information accessible by everyone is visible to the *public* (e.g., news). *Personal* information is restricted to the observer and a particular group of people (e.g. Facebook status posts). *Private* information is exclusively accessible by the current observer (e.g. private messages).

Visualization

When it comes to the visual output itself, designers have a large set of options. Tönnis et al. [98] defined six classes categorizing AR systems, which we adapted for our work.

Augmentation

Tönnis et al. also proposed the 'frame of reference', characterized by egocentric and exocentric presentation, as AR HUD presentation dimension. While the egocentric view corresponds to the driver's view, the exocentric view can be any other viewing position, e.g., the bird's eye perspective. The two frames of reference are included in the dimension *Augmentation* of our design space: *Reality & loose Information* includes the exocentric view, but also additional information that has no specific frame of reference, such as time. The egocentric view is part of *Augmented Reality (AR)* and *Virtual Reality (VR)*. *AR* corresponds to digital information merged into a person's view on the real world (spatially registered). *VR* is the immersive experience in a simulated world, the digital version of the real world or a completely virtual world.

Placement Strategy

This category describes the relative and absolute spatial placement of information. In their classification of AR HUD information presentation principles, Tönnis et al. [98] propose the class registration. They subdivide it into unregistered, registered and contact-analog. *Unregistered* information is placed without spatial relation to an environmental or in-vehicle object. Registered information is aligned with the real world but presented rather symbolic than naturalistic, according to Tönnis et al. On the other hand, contact-analog information is smoothly integrated into the real world and naturalistic; in a way that it looks and behaves like a real object.

'Contact-analog' is a term used exclusively in the car domain and often misused and confused with registered information placement. To address this, we propose the terms *2D registered* and *3D registered* and to distinguish naturalistic and symbolic information *presentation*. As *2D registered* we define information placed spatially close to a related object but not meeting its depth. As *3D registered* we define information placed at the same depth of and spatially close to a related object.

Tönnis et al. also propose glance behavior related information presentation [97, 98], which we consider here as a relative positioning strategy as well. *Gaze-dependent* information is placed relative to the observer's momentary visual focus point.

Field of View Position

We included this category in our design space as the windshield display wil – due to its size – not only address *foveal* and *central* vision but also *peripheral* vision. This is particularly important since humans' visual perception varies strongly within the field of view (FoV) [49, 60, 98]. In the area of *foveal* vision (up to 2° from line of sight) the human has the fastest and sharpest visual perception. Within the *central* field of view (up to 10°) colors, contours, and contrasts are still perceptible. In the *periphery* (beyond 10°) the human perception is mainly limited to movements, light alteration, and recognition of very simple objects and their orientation. When the driver looks straight at the road, the windshield ends approximately at 50°; this is where stereo-vision ends [1, 45].

One may argue that standard in-vehicle displays (instrument panels / CIDs) are also placed in the periphery when the driver looks straight on the road. However, the WSD may be too large to be fully perceived. Independent of where the user is looking, parts of the display are in the periphery. Furthermore, information on those standard displays is small-sized and thereby only perceptible by directly looking. In contrast, the WSD offers a lot of space to either display simple information large enough to make them perceptible, even with the limited peripheral perceptional abilities [49] (e.g. ambient information), or is actually meant to attain the driver's attention and lead it towards a hazard [47]. Of course, peripheral perception can be highly distracting and therefore needs to be used and designed carefully (see Haeuslschmid [46, 47] for a discussion).

Presentation

As already mentioned in category Placement Strategy, the information can be presented in a symbolic and a naturalistic way. *Symbolic information* 'embeds abstract symbols' [98]. This includes standard graphical elements such as text, (shapeless) forms, icons, abstract graphics, pictures, videos. *Naturalistic information* should not be identifiable as augmented to reality at first glance. It smoothly merges with the real world and looks and behaves like a real world object.

Graphic Design Factors

At first, this dimension only addresses graphics design, not the display technology. The standard design factors are dimensions by itself but grouped here to one since they are continuous or have few manifestations. Yet, designer need to be aware of them, when creating information for the windshield displays: *color*, *transparency*, *size*, and *motion*.

Color needs to be chosen carefully in the context of use (e.g., daytime), FoV position, and environment [14, 23, 39]. A common environment is a white to blue sky with a grey asphalt on the ground, possibly with greenish or brownish fields or also white or colored buildings to its sides. It is clear that colors which are well distinguishable from the background should be chosen to ensure recognizability. Furthermore, the cultural meaning of colors need to be considered [48].

Transparency is important since presented content can occlude the driving scene [74, 98]. It may be the case that driving-relevant objects in the surroundings should be highlighted (e.g. by light), but those objects should never be completely invisible to the driver. Here, transparency comes into play.

As mentioned earlier, objects placed in the periphery may have to be of larger *size* to be well perceivable and recognizable, independent of if they aim to gain attention or not. Research has to be performed in order to identify optimal sizes for information throughout the windshield display area.

Motion is directly related to relative information display. If information is displayed relative to an environmental object or also the driver's gaze, it is most likely that this information will have to move. Also animations, videos, and on-growing or blinking information belongs into this category. Motion is very distracting and has to be used carefully [14, 39].

Interaction

To enable interactive WSD applications, the potential WSD users also need to have the chance to interact with the system. The design space therefore also comprises dimensions that consider how to provide input to the system as well as additional (multimodal) output/feedback channels.

Input Modality

Kern and Schmidt [55] describe input and output modalities. They based their automotive design space on an analysis of the interior of modern (in 2007) and old cars and current trends. New interaction techniques, such as gesture and speech, are mentioned in the paper but not yet integrated into the design space due to the state of development at that time. Therefore, we now update this design space as follows:

The category *touch & controls* represents hand-based, haptic input techniques such as button, slider, knob, stalk control, thumbwheel, pedal, multifunctional controller, and touchscreens as mentioned by Kern et al. [55]. Charissis et al. investigated the control of a single-layer windshield displays using buttons [27]. Whether these controls are suitable to interact with multi-layer or continuous windshield displays has to be investigated. In particular, when the image is partially (3D) registered and unregistered and thereby dynamic and unstructured, far away from the common hierarchical layouts, it will be challenging to map controls with so limited dimensions. One possible approach is to mirror the driver's view through the windshield onto a touch sensitive display, as already proposed for other domains [87]. Touch on the windshield itself is not recommended due to the driver's limited range of motion and the size and orientation of the windshield. However, one could combine it for instance with (remote) touch interaction such as touch gestures on the steering wheel [35, 77].

Gestures, such as midair or micro gestures, are investigated intensively for in-car use. According to Fujimura et al. [40] and Rümelin et al. [79], pointing gestures are a good approach to interact with registered information such as points of interest. Though, it is unclear if gestures are suitable for more than one-handed interaction such as selection. Until (partially) autonomous driving is available, all users but the driver are free to perform two-handed gestures. Furthermore, entering text with gestures is problematic. More research has to performed to see if gesture-based input techniques (cf. Ni et al. [71]) are practicable and usable also in cars.

Speech is an input methodology of growing importance [9, 10]. It is a useful input method in cars but can most probably not be a stand-alone input method either, but, for example, be complementary to gestural interaction [77]. Since natural language understanding and analysis are not yet perfect and comprehensive in vocabulary, it will be difficult to select (the right) object by announcing it. Object manipulation and text input may be less problematic, though.

Gaze interaction is nowadays robust enough to be integrated in cars [73]. The driver's eyes are already tracked for apps such as drowsiness warning [104, 105]; this can be accounted as indirect input. Similarly, by implicitly storing and highlighting the screen location last looked at, attention switches away from and back to the screen can be accelerated [54]. Performing gaze interaction while performing another visual, safety-critical task requiring constant supervision is challenging. *Behaviour* can only serve as an indirect method of control for adaptive applications.

For interaction with the WSD from outside, future apps can draw from public display research. Most notably, touch, midair gestures, and phone-based interaction have beed explored in previous work [7, 33, 68]. More recently, also gaze was used as an interaction modality in public [56, 106].

Multimodal Feedback

According to Ablassmeier et al. [2], WSDs have a great potential for multimodal interaction concepts. We bases this dimension again on the design space by Kern et al. [55]. As the windshield display itself is a platform for *visual* output, here we only describe output modalities as extension to this. Visual feedback to a user action can of course be also displayed on other displays, e.g. a status LED, a head down display or also the windshield display of other road users. *Haptic and tactile* feedback can be given to the driver by means of vibration (e.g. seat belt or steering wheel) and also by airflow. *Auditory* feedback is given by means of loudspeaker and can range from a simple status change sound to a played music. *Olfactory* output has not been matter of research by now. Kern et al. propose to use it for ambient information [55].

Technology

In order to design the physical part of WSD apps, designers can choose from different technological options. These relate to how the image is generated, at which depth it is displayed, the WSD size as well as additional display factors.

Image Generation

By now, there are two major ways of generating a WSD image [46]: The first and simplest approach is to generate the *image directly on the windshield* itself: Either a (laser) projector is directed onto the windshield [36, 57, 102] or a transparent display such as OLEDs are integrated into the windshield [17]. This approach is advantageous compared to standard head down displays as the driver can keep the head up and the road situation in view while reading the display.

The second approach is based on the *reflection of a display or a projection surface on a transparent mirror*, called combiner, or the windshield. The image of a reflected light source seems to float above the road. The advantage is that the image distance is increased, which allows for faster eye accommodation and, hence, faster reaction time. Head-up displays are based on the principle of reflection: Betancur [15] describes several variations for constructing HUDs and WSDs. Also, the HUDs of major car manufacturers and contractors rely on this principle: Continental constructs HUDs for BMW, Audi, and Mercedes and describes the basic construction online [43]. Sato et al. [81] also used reflection but positioned a projector on the vehicle's roof, thereby enabling real world studies with a WSD of intermediate size. Takaki et al. [101] proposed a 3D HUD based on a reflected autostereoscopic multi-view display and reached a continuous image depth. The Pioneer HUD is a mobile realization which reflects the image to float 2.5 m behind the combiner, based on a DLP projector and a LED light source [37]. Lastly, there is research regarding future technology, e.g., 3D holographic image generation, which may soon find their way into cars.

Depth

Head-up displays normally present the image on a *single-layer* in front of the windshield [42] – perpendicular or angular to the road. This enables a 2D but no 3D registered information display. For a full AR feeling, digital information has to meet the depth of analog environmental objects. Hence, HUD research focuses on *continuous* depth presentation. Continuous displays are able to place images at various levels, which are not distinguishable for the observer, or at continuous depth. Therefore, the distances between the layers have to be within the boundaries of just noticeable depth difference (JNDD) [52]; Cutting et al. [32] provides measurements of JNDD based on monoscopic and stereoscopic depth cues. Furthermore, we propose to use the term *continuous* only in relation with a wide depth range, meaning that information can be presented 3D-registered to other road users.

Takaki et al. [101] built a WSD prototype enabling image presentation at distances up to 100 m. Broy et al. [20] and Charissis et al. [26], performed user studies on 3D HUDs with stereoscopic and hence (limited) continuous displays. Bark et al. [13] evaluated a vehicular navigation aid that uses a see-thru 3D volumetric HUD. However, these displays were only prototypes and cannot be integrated into production cars due to spatial requirements or limitations.

Between *single-layer* and *continuous*, we suggest the category of *multi-layer* technology. The layers of a display within that category are distinguishable for the observer and do not mandatorily have to be generated by the same technology. For example, a HUD can be combined with an OLED display. An example of information on two depth layers was presented by Blume et al. [16] and Continental [43].

Size

As mentioned before, WSDs can cover the entire windshield whereas HUDs are limited in and vary in size.

BMW HUDs have a size of $7.5 \times 17.5\,cm$ (in 2012) [18], Mercedes reports a reflected image size of $21 \times 7\,cm$ (in 2014) [62], and Pioneer documents a 29" projection image at a distance of 2.5 m [37]. In 2014, Continental announced HUDs at a size of 3.1" as new advancement as well as an AR HUD with an image size of $130 \times 60\,cm$ at a distance of 7.5 m [43]. In science, the size of the used display is rarely documented. Also, the constructional approach, such as the used light source, lenses, and image path, strongly influence the image size visible to the driver. Here, measuring the visible image in degrees (field of view) would be more self-explaining and independent of image distance.

We propose to categorize displays with a coverage of minimum 40 % horizontally and minimum 40 % vertically of the driver's windshield FoV as windshield displays. For displays of a smaller size we suggest to refer to them as head-up displays. We decided for a separation at 40 %, as smaller displays are most probably not able to cover the central road scene.

Display Factors

Standard display factors are dimensions by themselves but grouped since they are continuous or have few manifestations and so as to keep the design space concise. The light source (a display or projector) needs to fulfill requirements specific for in-car use. First, the light source has to be very bright to be visible in direct sunlight. HUDs have a luminance higher than $10{,}000\,cd/m^2$ [43, 62]. Furthermore, the *brightness* has to be adjustable to not glare at night, if the application is not daytime-dependent (e.g. night-vision). Another display factor to be considered is the display *transparency*. Currently, the windshield itself has to transmit at least 70 % of the outside luminance [80]. Technologies based on reflection or projection do not influence the light transparency of the windshield unless foils or covers are used. However, this does not mean that the visibility of outside objects is always ensured. With autonomous driving, this requirement may become less important. When the driver does not have to drive or supervise the car (level 4 automation), immersive virtual reality could be provided in cars. Together with more complex illustrations and larger display sizes, also the *resolution* and the *color space* of the display may need to increase. Current HUDs provide resolutions between 800 × 480 pixels [43] and 480 × 240 pixels (60 pixel per degree) [62]. As a final factor in this section, we also consider *color depth*. Display-based solutions normally feature full-color [37, 43, 62]. However, also uni- and bicolor laser-projector-based solutions exist [93].

USING THE DESIGN SPACE

We envision that the presented design space facilitates the design of interactive (windshield display) applications in and around the car. We seek to support the designers' creativity when designing novel systems for a specific use case. Using the design space, they can easily explore the multiple dimensions for windshield displays in order to define the technical implementation. By comparing and discussing the available options in each dimension, differences between designs can be understood. Also, by considering the multitude of options new ideas, use cases, and approaches may be identified.

In the following we present two exemplary thought experiments to showcase how the design space may support the design process for interactive vehicular applications. For both examples, we first present a motivation and explanation of the use case. We then present the discussion of the use case from a designer's point of view.

Example 1: Pedestrian Navigation

Navigation is a frequent task when driving a car. Today, various solutions for navigation exist, including convenient WSD applications and visualizations. Navigation is also of interest to pedestrians and cyclists who often use their smartphone for this purpose. Considering the option to display information to people outside the car, WSDs may also be beneficial for the latter user group: Constantly pulling out and unlocking the phone is annoying. Furthermore, it can be cumbersome to view a larger map or plan a longer trip on the small phone display. Using the outside WSD of a car, one could create a new navigation system for pedestrians which integrates the outside projection windshield display as an extension to the personal phone (see also Figure 1).

Paul is a designer, using our design space to develop the presented WSD application. He imagines the following scenario: A group of people walks around an unfamiliar city to explore its sights. They want to locate themselves and find the shortest way to the central square. Using a printed map is old-fashioned and so is it to use the smartphone for navigation. Instead, the group steps towards a parked car and one of the group's phones connects to the car. The outside WSD displays the city map. Once someone enters the next destination, the map presents the most interesting or shortest route to get there. The group then starts out to the central square.

How could this application look like? When the scenario is defined, Paul explores how the application idea could be further expanded and designed. 'In my scenario a *group of people* walks through the city', Paul thinks. 'Of course, it could also be a *single* person. Would it make a difference in designing the application? Probably not, as long as everybody is *inside or outside* the car – and the *display technology* enables it, of course. And also, only because there are several *observers*, it does not mean that everybody wants to interact with the system. Actually, does anyone need to interact with the system once the destination is entered? This depends on which other functions the system provides. Are there other ways to *visualize* the path? Once the group starts, cars on the way could *dynamically* light the way to the central square – serving as *ambient* displays. Does this also work on driving cars, or only with *parked* ones? Well, it could work with both. Those displays could also react to the pedestrian's *gaze* – maybe by presenting an arrow that points to the right direction. But eye tracking might be difficult to implement: Light conditions could impede the detection. And: sensors need to be clean. At least I don't have to be concerned about *privacy* issues when the application only presents general information which is not even obviously connected to a particular person. What if several groups are walking around the city using the same app? That's definitely something I have to consider carefully– later. Let's discuss another dimension. Which other content or features can be nice and practical for visitors? The application should be more *entertaining*! That helps to make the journey more fun and adventurous. When exploring the city, it could be nice to get historical information – or to see how this particular place looked like a century ago. Even better, the group could be on a treasure hunt. I always enjoy treasure hunting. The app could only tell where to turn next when a question was answered correctly. It could actually *tell* the directions by giving *auditory feedback*. Maybe the users talk with an avatar. Which other *input modality* could they use? To move the map or to select something, touch would be perfect. But wait, the hood is in the way. Actually, I wouldn't like to have greasy finger prints on my freshly washed car. What happens if the owner of the car is still inside? Maybe (s)he is also interacting with the display – looking up when it will stop raining. Well, better no touch interaction on the windshield. But maybe touch interaction on the personal phone? But I wouldn't want to take it out of my pocket. So, maybe *speech* and *gestures* could do. Okay, that's good for now. '

Example 2: Driver Training

Most car accidents (appr. 90 %) are caused by human error [91]. That is why a lot of effort is spent on training – particularly young drivers but there are also specific driver training for all drivers to train for emergency situations. However, the reason for an accident is often the driving behavior, for instance hubris or underestimation of danger.

'When I was young, I already felt being a good driver – a bit arrogant maybe – and I even drove intoxicated sometimes. My girlfriend instead was shy and overcautious – anything but a good driver. Now that I think about it, I would have actually needed a resolute girlfriend rather than more training. I am pretty sure that there are many people who are like I was back then. How could I design an application for a *single user* suitable for both, arrogant and overcautious drivers?'

'First, new drivers need to familiarize with the car regarding size, steering, and reversing. Virtual lines and arrows could help the student. This *visualization* already exists – but actually it is boring. I think the application also has the *purpose* to *entertain*. When drivers are emotionally involved, they benefit more from this training session. So let's look for something unconventional – something they enjoy. Let's replace the virtual lines – maybe by coins just like in Super Mario. When drivers perfectly keep the lane, they get feedback by this nice sound of rattling coins. Let's see some other feedback *modalities*: We could use haptic feedback in addition to that. For instance, the steering wheel vibrates if the driver performs badly.

I think that is a nice start when learning to drive but after a certain *time* it is not challenging anymore. What is really difficult is to learn is how to react in emergency situations. It's hard to fake them. But when they happen in real life, you better know what to do. Since *AR* is already available, there might be the opportunity to artificially create such situations, for example, in a playful application during automated driving – wild animals or pedestrians that cross the road could appear. But where should they appear? The design space says, visual perception is limited in the *periphery* – so why not there? And the student has to detect them and to react properly. But to display one after the other is not surprising. This should depend on something. Let's look at the *input modalities* for this: bad *behaviour* and *gaze* – looking away from the road – can trigger the emergency. But the *presentation* has to be very naturalistic, otherwise it is too easy to spot that it is artificial.

Are there advantages or new opportunities when using *VR* instead of AR? Yes – we could completely influence their vision by that! When already creating emergency situations, we could use VR to demonstrate how dangerous intoxicated driving is. The windshield could be *blurred and dimmed* around the driver's *gaze* point. That could be tested at *night* when they are tired. In this condition, they have to repeat the previous test and see how their spatial and hazard detection performance is impeded.'

Summarizing the two presented thought experiments, 'Paul' explored the dimensions and characters of the design space which encouraged him to look at the ideas from different angles. With the proposed design space at hand, he created a lot of new ideas for already existing concepts.

DISCUSSION AND LIMITATIONS

Based on our extensive literature research and patents review, we defined our design space to be as inclusive and comprehensive as possible. However, we are aware that neither the list of applications nor the categorization provided may be complete.

Due to the composition of our focus groups, the findings reflect the view of a rather young age group with a strong focus on communication and entertainment. However, we believe young, tech-savvy drivers to be a major user group of WSD apps. At the same time, conducting additional focus groups with other age groups may identify further use cases. While middle aged users may be interested in applications related to or supporting their work, older users may benefit from applications that focus on increasing road and driving safety.

Windshield displays is still a young research field. Only as the technology required to build interactive, large-sized windshields matures it will become possible to investigate the impact of technical properties (e.g., depth continuity). Furthermore, with advances in technology, new opportunities and ideas will arise and lead to an extension of our initial categorization of the design space. Examples include, but are not limited to new interaction devices or novel output technology (for instance holography) or changes with regard to mobility concepts (car sharing, electric vehicles). Also, we are aware that not all provided options may be in compliance with legal requirements at the time of publication of this work. For instance, there may be limitations with regard to the degree of transparency of the WSD, its (dynamic) content and its brightness towards the outside of the vehicle.

To show how the design space could support designers in creating novel applications for WSDs, we provided two example use cases. As these showcases are only thought experiments, it is still unclear how the design space will actually be used and how designers benefit from it.

CONCLUSION

Based on two examples, we showcased how the design space for windshield display applications presented in this paper can aid the design process for future vehicle systems, in particular by enabling design alternatives to be compared and discussed as well as by encouraging and supporting the designer in exploring novel aspects. Furthermore, we presented the different application categories which supports the ideation process as practitioners and researchers explore novel application areas.

The design space allows to explore the different dimensions, both for inside and outside WSD. As the idea of using windshield displays from the outside further evolves, we see a tight connection to the research area of public displays. Researchers need to think of how to attract the attention of passersby and how to communicate that interaction is possible with the windshield display – which currently nobody would expect. Further, such displays would need to offer easy-to-use and easy-to-understand interaction techniques – presumably beyond touch, as has been stressed before – and such displays would need to motivate people to approach and use them. Ultimately, novel business models emerge where vehicle owners could be reimbursed for sharing the interaction space – both by the providers of applications as well as by the users of these applications.

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