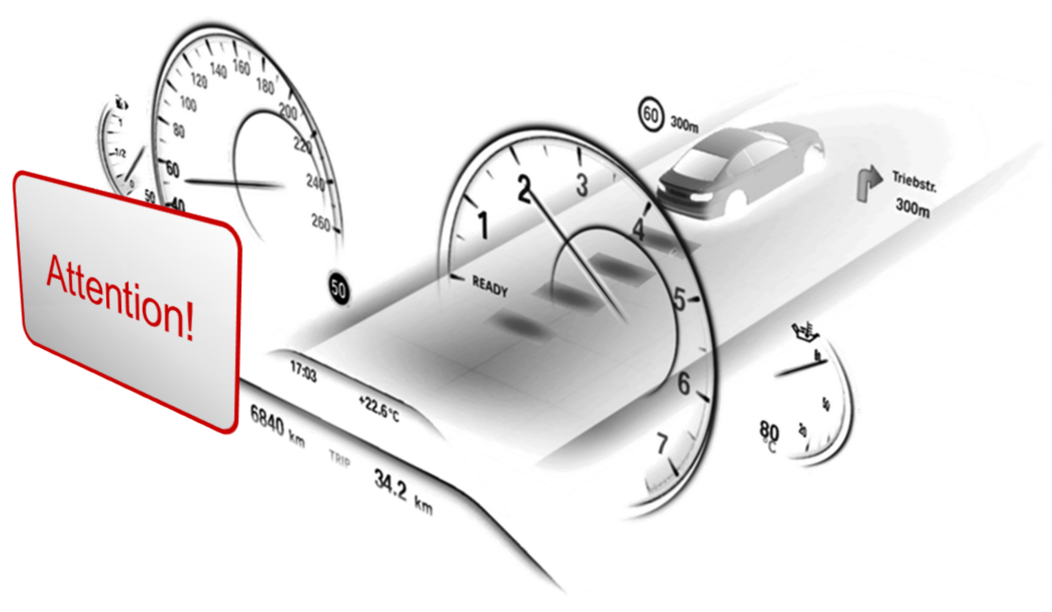
Stereoscopic 3D User Interfaces

Exploring the Potentials and Risks of 3D Displays in Cars

Nora Broy



Universität Stuttgart

STEREOSCOPIC 3D USER INTERFACES

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ABSTRACT

During recent years, rapid advancements in stereoscopic digital display technology have led to acceptance of high-quality 3D in the entertainment sector and even created enthusiasm towards the technology. The advent of autostereoscopic displays (i.e., glasses-free 3D) allows for introducing 3D technology into other application domains, including but not limited to mobile devices, public displays, and automotive user interfaces – the latter of which is at the focus of this work. Prior research demonstrates that 3D improves the visualization of complex structures and augments virtual environments. We envision its use to enhance the in-car user interface by structuring the presented information via depth. Thus, content that requires attention can be shown close to the user and distances, for example to other traffic participants, gain a direct mapping in 3D space.

The core question of this thesis is whether and how stereoscopic 3D can contribute to advanced automotive user interfaces. In particular, there are three major research challenges that need to be tackled for a reliable answer. First, the 3D effect is well known for inducing discomfort to some users. So far, there are neither common principles nor guidelines for beneficially applying stereoscopy to graphical user interfaces. Second, the agile and quick development of spatial layouts is challenging as common prototyping techniques do not support the exploration of 3D space. Third, potentials and risks of the deliberate use of the 3D effect for in-car displays need to be evaluated. This thesis provides solutions to overcome these challenges.

First, we present several user studies to understand viewing comfort as well as depth perception using 3D displays. Based on the use of abstract perceptual tasks and highly controlled laboratory setups, we formulate a set of concrete design principles, which are fairly independent of a specific application domain. We deliberately explore stereoscopic 3D for structuring the displayed content and for augmenting the real world. In particular, we demonstrate the application of the design principles to an automotive instrument cluster and head-up display.

Second, we introduce tools that support the designer in prototyping and evaluating stereoscopic user interfaces. These tools address solutions for paper prototyping as well as computer-based prototyping and incorporate the previously defined design principles. An evaluation with user interface designers shows that our tools promote the creative exploration of 3D layouts.

Third, with the help of the principles as well as the tools we come up with 3D applications for a digital instrument cluster. As user interfaces for highly automated driving have requirements beyond those for manual driving, we investigate the use of stereoscopy for both driving modes. For manual driving, simulator as well as real-road studies prove various advantages of stereoscopy in terms of presenting spatial information (e.g., navigation cues), visualizing the urgency of content elements (e.g., popping-out warnings), visual decluttering of the display, and an increasingly joyful interaction. Moreover, we could not find evidence for an increased visual load nor driver distraction due to the 3D effect. Pertaining highly automated driving, we evaluate the impact of a non-driving related task which exhibits a 3D layout on the take-over behavior of the driver. We show that a 3D layout similar to the current road scenery can improve the driver's reengagement in the driving task.

In conclusion, this thesis broadens the understanding of layered 3D interfaces and proves explicit advantages for in-car 3D displays. This makes 3D displays attractive candidates for future vehicles, under the assumption that display quality of autostereoscopic technologies will be further improved. The results of this thesis should motivate future research and support practitioners in developing innovative 3D technologies and applications inside as well as outside the car.

ZUSAMMENFASSUNG

Die rasante Entwicklung stereoskopischer Displaytechnologien hat in den letzten Jahren zu breiter Akzeptanz von 3D Darstellungen in der Unterhaltungsbranche geführt. Autostereoskopische Displays (brillenlose 3D Displays) ermöglichen die Verwendung der 3D Technologie in weiteren Sparten. Beispiele für potentielle Anwendungsfelder sind mobile Endgeräte, Werbung auf öffentlichen Bildschirmen sowie Anzeigen im Automobil, wobei letzteres im Fokus dieser Arbeit steht. Es ist bekannt, dass der 3D Effekt die Darstellung von komplexen Informationsstrukturen vereinfacht und die Interaktion in virtuellen Welten bereichert. Somit kann der 3D Effekt dazu beitragen eine bessere Strukturierung der Anzeigeinhalte im Fahrzeug zu erzielen. Dem Fahrer können Informationen, die seine besondere Aufmerksamkeit erfordern, räumlich näher angezeigt und Distanzen, zum Beispiel zu anderen Verkehrsteilnehmern, analog zur Fahrszene im 3D Raum abgebildet werden.

Die zentrale Fragestellung dieser Arbeit ist, ob und wie stereoskopisches 3D die Benutzerschnittstelle im Fahrzeug verbessern kann. Um diese Frage zu beantworten, stellt sich diese Arbeit drei forschungsrelevanten Herausforderungen. Zum einen ist der 3D Effekt dafür bekannt, Beschwerden wie zum Beispiel Kopfschmerzen, hervorzurufen. Zum anderen ist die Entwicklung von räumlichen Darstellungen komplex, da typische Techniken zur schnellen Erstellung von Prototypen die Exploration des 3D Raums nicht unterstützen. Letztendlich, gilt es Potentiale und Risiken des wohlbedachten Einsatzes von 3D Displays im Fahrzeug zu identifizieren und mit wissenschaftlichen Methoden zu bewerten.

Im ersten Schritt untersucht diese Arbeit den Betrachtungskomfort sowie die Tiefenwahrnehmung von stereoskopischen Darstellungen. Basierend auf grundlegenden Nutzerstudien werden konkrete Prinzipien zur Strukturierung von Informationen mittels Stereoskopie und zur virtuellen Augmentierung der realen 3D Welt gegeben. Durch den Einsatz abstrakter Wahrnehmungsaufgaben unter kontrollierten Laborbedingungen sind diese Ergebnisse zunächst unabhängig von einem spezifischen Anwendungsbereich. Zugeschnitten auf das Automobil wird die Verwendung der Gestaltungsprinzipien am Beispiel eines Kombiinstruments und Head-Up Displays demonstriert.

In einem zweiten Schritt werden Werkzeuge erarbeitet, durch die der Entwickler stereoskopische Benutzerschnittstellen prototypisch realisieren und evaluieren kann. Diese Werkzeuge ermöglichen die Umsetzung von Papier- sowie Softwareprototypen. Eine Expertenbewertung der entwickelten Werkzeuge zeigt, dass die zur Verfügung gestellten Hilfsmittel dem kreativen Entwicklungsprozess von 3D Anwendungen unterstützen.

Basierend auf den erarbeiteten Gestaltungsprinzipien und den entwickelten Werkzeugen werden 3D Anwendungen für ein digitales Kombiinstrument realisiert. Da hochautomatisiertes Fahren grundsätzlich andere Anforderungen als manuelles Fahren an die Benutzerschnittstelle stellt, wird der Nutzen des 3D Effekts für beide Fahrmodi bewertet. Hinsichtlich des manuellen Fahrens werden Simulator- als auch Realfahrzeugstudien durchgeführt. Die Studien weisen eine Reihe von Vorteilen einer stereoskopischen Darstellung nach. So werden die Darstellung räumlicher Elemente (zum Beispiel von Navigationshinweisen), die Visualisierung dringlicher Inhalte (zum Beispiel von Warnungen), die Strukturierung der angezeigten Informationen und die Attraktivität des Systems durch den 3D Effekt verbessert. Dabei kann keine erhöhte kognitive und visuelle Ablenkung des Fahrers durch die 3D Darstellung festgestellt werden. Für das hochautomatisierte Fahren wird der Einfluss einer fahrfremden Tätigkeit, die eine Interaktion mit einem 3D Display verlangt, auf die Übernahmefähigkeit des Fahrers bewertet. Eine Fahrsimulatorstudie zeigt, dass die Interaktion mit einer 3D Darstellung, die der räumlichen Beschaffenheit der Fahrszene ähnelt, den Fahrer in der Übernahme der Fahraufgabe unterstützt.

Diese Arbeit zielt auf grundlegende Beiträge zur Entwicklung stereoskopischer Benutzerschnittstellen und zeigt explizite Vorteile einer 3D Anzeige für automotive Anwendungen auf. Unter der Hypothese, dass sich die Anzeigequalität autostereoskopischer Technologien in der Zukunft verbessert, stellen 3D Displays attraktive Anzeigekonzepte für zukünftige Fahrzeuge dar. Aktivitäten in Forschung und Praxis sollen durch die Ergebnisse dieser Arbeit motiviert und unterstützt werden, innovative 3D Technologien und Interaktionskonzepte für Anwendungen innerhalb und außerhalb des Fahrzeugs zu entwickeln.

PREFACE

This thesis is the result of the research I carried out at BMW Research and Technology, the University of Stuttgart, and the University of Munich from 2012 – 2015. As a dissertation cannot be created in isolation, all of my decisions were strongly influenced by innumerable conversations and discussions with my colleagues at BMW and at the Universities. In the context of this work, I supervised several Bachelor and Master thesis which supported me in realizing my ideas. Parts of this thesis report on projects which are based on the fruitful collaboration with Bosch and SeeFront. In all stadiums of my work, the exchange with researchers and practitioners at occasions such as conferences, workshops, and lab visits, was invaluable and inspiring. As a result, I chose to write this thesis using the scientific plural. The presented work is partly based on scientific papers. The resulting publications are referred at the beginning of the respective chapters.

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LIST OF ACRONYMS

AAM	Alliance of Automobile Manufacturers
AC	accommodation-convergence
ACC	Active Cruise Control
AR	augmented reality
ANOVA	analysis of variance
ATTR	attractiveness
CAD	computer-aided design
CID	central information display
DALI	Driving Activity Load Index
DDT	deviation of driving trajectory
ESOP	European Statement of Principles
GUI	graphical user interface
HCI	human-computer interaction
HMD	Head-Mounted Display
HMI	human-machine interaction
HQ	hedonic quality
HUD	head-up display
IC	instrument cluster
IR	infrared
ISO	International Organization for Standardization
IVIS	in-vehicle information system
JAMA	Japan Automobile Manufacturers Association
LCT	Lane Change Task
MLD	multi-layer display
NHTSA	National Highway Traffic Safety Administration

PQ	pragmatic quality
rpm	revolutions per minute
RDS	Random-Dot Stereogram
S3D	stereoscopic 3D
SSQ	Simulator Sickness Questionnaire
SDLP	standard deviation of lateral position
SUS	System Usability Scale
SuRT	Surrogate Reference Task
TCT	task completion time
TOR	take-over request
TTC	time to collision
UI	user interface
UMTRI	University of Michigan Transportation Research Institute
VSD	virtual screen distance
VID	virtual image distance

I

INTRODUCTION AND MOTIVATION

Chapter 1

Introduction

We live in a three-dimensional (3D) world. Humans make use of their senses in order to orient in, to move through, as well as to interact in these three dimensions. One of the most important human sensors for enabling an internal representation of the spatial environment are the human eyes. The role of two eyes have been subject of scientific speculation for centuries. 300 years B.C. Euclid's treatise on *Optics* has already described that both eyes have slightly different views on three dimensional objects [98]. In the 15th century Leonardo Da Vinci elucidated the phenomenon of binocular vision in his book *Trattato della Pittura* as follows:

> *"A painting, though conducted with the greatest art and finished to the last perfection, both with regard to its contours, its lights, its shadows and its colours, can never show a relievo equal to that of the natural objects, unless these be viewed at a distance and with a single eye."*
>
> – **Leonardo Da Vinci** (ca. 1500) [244]

In comparison to Euclid, Da Vinci went in his description one step further: He realized binocular vision as a source of information about depth [98].

1.1 The Fascination of Stereoscopic 3D

3D always fascinated and attracted audiences. At the time of Da Vinci, perspective drawings as well as the perfect use of texture gradients and shadows delivered an impression of depth. In 1838, Charles Wheatstone introduced a device, the stereoscope, which allowed two different images to be presented to the eyes at the same time [98]. He provided several line drawings of stereo pairs that could be viewed as solid objects using his stereoscope [98, 267]. Thus, he proved that the perception of a solid three dimensional object is the result of simultaneously showing two dissimilar plain pictures to the retinas. Stereoscopy, the technique to create the illusion of depth on a screen, was born. The invention of the stereoscope and photography led to the golden age of stereography from 1870 to 1920 [267]. Stereoview cards became mass entertainment, for example, in the form of postal cards and stereograph sets featuring narrative sequences, usually comics. With the advent of motion pictures, stereoscopic 3D (S3D) visualizations entered the movie industry. Around 1950, 3D cinema screens proved to be an important differentiation from home entertainment which emerged with the availability of TV sets for the living room [268]. The rising hype of 3D cinema, called the “1950’s golden age of 3D”, passed quickly since technical difficulties in production and exploitation resulted in poor 3D viewing experiences [153].

Advances in digital production and projection technologies enabled high quality 3D and has established stereoscopy in cinemas and home entertainment since 2005 [153, 268]. The statistics of the Motion Picture Association of America[1] show that the digital 3D proportion of total digital cinema screens constantly grew from 2010 with 22% until 2014 with a global proportion of 51%. The increase in computation power and signal processing, low-cost high performance graphics cards, and growing screen resolutions allowed 3D to become ubiquitous. Additionally, the advent of autostereoscopic displays, providing the viewer a 3D experience without any headgear, facilitates the ongoing proliferation. TVs enable watching 3D movies [171, 212], laptops allow for playing 3D games [146, 206], mobile phones can be used to create and show 3D images or clips [80, 86, 224], see through head-mounted displays offer a 3D augmentation of the real world [118,229], and public displays use stereoscopic content to attract the audience [47]. For these applications, stereoscopic visualizations improve the user experience and immersion [206, 228] and the natural as well as spatial perception of the image. Indeed, from the invention of the stereoscope until today, stereoscopic presentations have excited and provided peaks in mass entertainment.

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[1] http://www.mpaa.org/wp-content/uploads/2015/03/MPAA-Theatrical-Market-Statistics-2014.pdf, last accessed September 24, 2015.

Besides the entertaining character of 3D, it proved to be useful in medicine, industrial design, and the military [149]. One of its most impressive applications was its usage in World War II in order to fight against Germany [119]. British Spitfires were equipped with cameras instead of weapons and took millions of pictures of German terrain. A team of photographic interpreters analyzed the recordings using a stereoscope. The 3D effect allowed them to identify German rockets and their launch sites, which were almost impossible to discover on a 2D photography. In this way, the Allies could directly attack the imminent threat.

1.2 Automotive Displays

Around 130 years ago, the automobile was invented. This was the beginning of a new era of transportation with motor vehicles as comfortable and individual means for mobility. While the very first cars had no displays, their increasing adoption as well as advances in technology (e.g., increasing maximum possible speed) required the introduction of petrol and speed gauges as well as indicators to reduce accidents. The instrument cluster (IC) was born. Today, various controls and displays inside the car provide access to detailed vehicle and environmental information, driver assistance systems, entertainment, as well as the internet. To handle the vast amount of information, modern cars are equipped with digital displays in the center stack, show most important driving information in a head-up display (HUD), and increasingly make use of digital display technologies for the IC. The driver has to manage these in-vehicle information systems while driving. Although automated driving is almost ready for takeoff, currently drivers still need to drive on their own, which will be mostly the case in the near future, as well. An appropriate interaction design, structure, and visualization of the data is significant for an intuitive, simple, and also joyful interaction which simultaneously ensures safe driving. The visual output is a key aspect of the user interface (UI) as maneuvering a vehicle particularly relies on the driver's visual perception. Therefore, visual distraction and glance durations on in-car displays need to be reduced to a minimum. Hence, a well structured visual display supports the driver in assessing the intended information intuitively and rapidly. We envision the use of stereoscopy for enhancing the structure of the displayed content to foster a pleasing, intuitive, and fast interaction with the in-car UI.

The automotive industry has already made use of a 3D effect for enhancing their in-car displays. Analogue ICs often show three-dimensional arrangements of their elements as the examples in Figure 1.1 illustrate. Typically, gauges embody

(a) BMW 1800[2] (b) Audi R8 GT[3]

Figure 1.1: Analogue instruments in the car often exhibit a 3D shape.

a 3D layout with a needle hovering over a dial. While the BMW 1800[2] (cf., Figure 1.1(a)) embeds its 3D shaped gauges into the dashboard, the Audi R8 GT[3] (cf., Figure 1.1(b)) further separates its 3D gauges in depth. However, modern cars are increasingly equipped with fully digital ICs displaying a vast amount of information on one 2D plane. In consequence, several automotive manufactures and suppliers presented show and concept cars that involve stereoscopic 3D or layered displays to overcome the flat nature of 2D displays. Examples for stereoscopic automotive displays showed Mercedes and Jaguar Land Rover showcasing autostereoscopic displays as IC[4]. The KIA GT concept[5], which uses three transparent OLED displays, and the Multilayer Instrument Cluster of Johnson Control[6] display driving information on separate depth layers. Although the aforementioned demonstrations use different display technologies, they all aim at prioritizing information via depth by locating important and urgent information at a foremost layer. As these high-fidelity prototypes prove the technological feasibility of in-car 3D displays, little is known about interacting with 3D representations while driving.

To lay the scientific foundations, we identified the core research questions in order to evaluate the potential of 3D displays and their particular application in cars. We developed several low- and high-fidelity prototypes demonstrating the use of binocular depth cues. The evaluation of these prototypes in laboratory, driving simulator, as well as real world settings allowed us to identify potentials and risks of an in-car use of 3D displays.

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[2] picture taken from http://www.automobilemag.com, last accessed September 24, 2015.

[3] picture taken from http://cartype.com, last accessed September 24, 2015.

[4] http://www.seefront.com/cases/, last accessed September 24, 2015.

[5] http://www.kia.com/eu/future/kia-gt/, last accessed September 24, 2015.

[6] http://www.presseportal.de/pm/19526/2185730, last accessed September 24, 2015.

Table 1.1: Summary of Research Questions.

Research Question	No.	Chapter
I. Design Principles		
Which 3D layout supports a comfortable viewing experience?	(R1)	Chapter 4
How do 3D parameters affect the depth perception?	(R2)	Chapter 5
II. Prototyping Tools		
How can we extend paper prototyping for 3D user interfaces?	(R3)	Chapter 6
How can computer-based tools support prototyping for 3D displays?	(R4)	Chapter 7
III. Automotive Application Domain		
How does 3D depth impact on task performance while driving?	(R5)	Chapter 8
How do drivers perceive the 3D effect while driving through the real world?	(R6)	Chapter 9
How does 3D influence the take-over behavior for highly automated driving?	(R7)	Chapter 10

1.3 Scope of the Thesis

The scope of this thesis is to explore the challenges as well as opportunities of using S3D visualizations in cars. Consequently, the focus lies on the introduction of the visual stereoscopic output technology to in-car UIs rather than on investigating novel input concepts for interacting in 3D space. In addition, we deliberately target the automotive context but also discuss where results are applicable to other application areas of 3D displays, for example, mobile devices.

1.4 Research Questions

To fully understand the potentials and risks of in-car 3D displays, we initially tackle questions that are of a more general nature before focusing on questions which concern concrete automotive use cases. In summary, our research is based on three major steps that increasingly approach the object of investigation, namely an in-car stereoscopic UI (cf., Table 1.1).

Despite its fascinating appeal, S3D is known to cause uncomfortable feelings, for instance, headache or nausea [129]. Such symptoms rise from the used display technology or the presented 3D content. Disturbing visual artifacts and incautiously chosen content parameters (e.g., an extreme depth budget) can even destroy the viewer's depth perception. In a first step, it is necessary to identify optimal design parameters that maximize both the viewing comfort (R1) and the user's depth perception (R2).

In a second step, developers should be able to exploit the potentials of 3D while observing the identified parameters. Creating UIs for 3D displays requires technical expertise and considerably more effort compared to developing for conventional 2D displays. To come up with ideas and conducting quick iterations, prototyping is a powerful approach. There are many tools that perfectly support the development of 2D UIs, for example, Balsamiq [63] or Axure [210]. So far, there are none that easily allow the use of paper (R3) or software (R4) for quickly prototyping 3D layouts.

As a third step, we deliberately investigate potentials and challenges of a 3D display as an automotive IC. Thereby it is essential to understand the impact of a well-considered 3D UI while driving. The driving simulator provides the perfect environment for an initial evaluation of the influence of stereoscopic presentations on the primary driving task as well as on secondary tasks (R5), for example, reacting to unexpected events displayed in the IC. Although the driving simulator represents a valuable evaluation method for novel automotive UIs, real world driving tests (R6) are necessary for a holistic comprehension [190, 202]. Research about automotive UIs for manual driving scenarios focuses on the dual task paradigm. With the advent of highly automated driving, the requirements of in-car UIs shift. As a look into the future, we are interested in the use of a S3D application while highly automated driving and the resulting driver behavior, when it comes to a vehicle initiated take-over request (R7).

1.5 Methodology

Although scientists have investigated stereoscopy over 175 years, research about its usage for enhancing graphical user interfaces (GUIs) is relatively new. In 1995, Harrison et al. [85] presented the concept of *layered user interfaces*. They state that information on different transparent depth layers supports the user in focusing attention on a single UI object and in dividing attention between multiple objects. As we envision the utilization of 3D displays to structure information on several depth layers, this work mainly draws upon their concept. Around 2005, prices for high quality stereoscopic display technologies dropped and the use of stereoscopy could be exploited for various application domains. But until today, there is no common understanding of how to use stereoscopy for enhancing GUIs. In particular, its impact on in-car UIs has not been studied yet.

Due to the lack of commonly accepted design principles for stereoscopic interfaces, we followed a bottom-up approach. This means that we started with identifying general design principles before refining those in the context of particular applications in the car. During three years, small and medium scaled projects addressed challenges and identified new research directions. The results contribute to the development of stereoscopic applications as well as automotive UIs. Following a user-centered design approach, we iteratively developed prototypes by incorporating user feedback at all stages of the development process.

1.5.1 Human Factors

Throughout this work, we were mainly concerned with the influence of 3D presentations on the human perception and behavior. The investigation of such effects required knowledge of several disciplines such as psychology, computer science, engineering, physics, as well as industrial design. A thorough literature review as well as a close collaboration with experts from industry and research bridged the substantial knowledge gap between the involved disciplines.

1.5.2 Prototypes

We built several prototypes with the ultimate goal to gather user data in laboratory, driving simulator, and real-road tests. The fidelity of the prototypes ranged from rudimentary and abstract depth layouts to interactive systems running in a real vehicle. We chose the fidelity of the prototypes in regard to our research questions. In particular, the high-fidelity prototypes for testing the 3D effect on real roads required excessive effort to ensure robustness, reliability, and road safety.

1.5.3 Evaluation

In the center of developing a user-friendly system we need to consider the user, in our case the driver and their needs. Accordingly, we carried out several user studies to answer our research questions. First, we used highly controlled laboratory setups built up with an automotive application in mind. The goal was to provide findings that could be generalized to further application domains. Second, we developed tools which should support developers in creating 3D UIs and evaluated our developed concepts with experts in UI design. Third, we applied standardized as well as established methods for evaluating the in-car use of 3D displays. Thereby, driving simulators allowed us to obtain results of high internal validity. Therefore, we used the simulator infrastructure at BMW which provided simulators of different fidelity. Based on the investigated research questions and our hypotheses, we chose the appropriate fidelity, which ranged from a simple vehicle mockup in front of a TV showing the driving scenery to a dynamic simulator providing kinesthetic feedback, a field of view close to 360°, and a full vehicle mockup. Fourth, we conducted real-road studies in order to complement our findings with results of high external and ecological validity. Therefore, we put emphasis on maximizing the safety of our study participants.

Allover, we gathered objective and subjective as well as quantitative and qualitative data by using a broad set of methods and tools, including focus groups, heuristic evaluation, interviews, data logging, questionnaires, as well as observations. For a statistical analysis, we used accepted approaches as they are reported in relevant literature, e.g., Bortz [16] and Pallant [174]. We applied a significance level α of 5 % for all tests and used non-parametric alternatives if appropriate.

1.6 Summary of Research Contributions

To answer the question of how 3D displays can be used in automotive UIs, this thesis makes three main contributions that are also transferable to further application domains such as mobile devices: First, we define design principles that recommend how to maximize the viewing comfort, user performance, and the user experience in 3D depth. Second, we provide prototyping tools facilitating the development of stereoscopic UIs and the observation of the defined design principles. Third, we present potentials and challenges of an in-car use of 3D displays based on S3D IC prototypes, developed by applying both the identified design principles and our prototyping tools.

1.6.1 Design Principles

Based on a literature review and several laboratory studies, we identified design principles which form the basis for recommendations on how to use depth to maximize the user experience, performance, as well as viewing comfort. Special attention was given to providing insights into how information can be structured on multiple depth layers. Therefore, we considered two typical display locations in the car: the IC commonly located behind the steering wheel and the HUD, which projects information into the driving scene. These display locations cover both near viewing and far viewing distances. To address a variety of application domains we kept the tasks of the user studies mainly abstract. The resulting principles include recommendations about the use of stereoscopic parameters as well as depth cues for arranging objects in 3D space.

1.6.2 Prototyping Tools

The development of UIs for 3D displays as well as the observation of the stated design principles require a lot of technical expertise. The design space of 3D is considerably more complex than for a plane display since there is one additional parameter, stereoscopic parallax, which has to be considered carefully. Existing prototyping tools and methods do not support the exploration of 3D space and do not meet requirements which have to be inherently addressed when prototyping for 3D displays. In order to close this gap, we developed prototyping tools supporting the development for 3D depth in early stages. In particular, these tools support the design of multiple depth layers. All proposed tools were developed in a user-centered design process and evaluated with expert users. Table 1.2 provides a summary of the developed tools.

Table 1.2: Summary of the Developed Prototyping Tools

Prototyping Tool	Description	Chapter
FrameBox	The FrameBox is a cubic box with a number of slots that represent different depth layers. UI elements made out of a large variety of materials, including paper and transparency films, can be positioned on those depth layers. We chose the positions of the depth layers in accordance with our proposed design principles. In this way, developers can use the FrameBox for easily creating 3D paper prototypes.	Chapter 6
MirrorBox	Using semi-transparent mirrors, the MirrorBox allows prototyping on three virtual depth layers. Thereby the user can choose to sketch the three layers on transparency films or on a 2D display with computer-based graphics editors.	Chapter 6 & Chapter 7
S3D-UI Designer	We developed a software architecture that allows multiple depth layers to be digitally prototyped with an instant visualization on a 3D display. A first implementation of the S3D-UI Designer applies the MirrorBox as 3D output device and allows to choose between two working environments for designing the depth layers, a traditional desktop environment and an interactive tabletop.	Chapter 7
S3D-HUD Designer	The S3D-HUD Designer provides a virtual 3D environment in which the user can prototype a 3D head-up display by directly integrating UI elements. The tool allows the positioning and manipulation of UI elements using mouse and keyboard as well as mid-air gestures.	Chapter 7

1.6.3 Application in the Automotive Domain

We applied both the defined design principles as well as the prototyping tools during the process of creating concrete 3D concepts for an IC in the car. We installed those concepts in vehicle mock-ups as well as in a real car and conducted driving studies in the simulator and on real roads. Our studies show that a 3D presentation outperforms a plane 2D visualization in many aspects. Although 3D does not have a significant impact on the primary driving task it increases the user experience, offers means of communicating the urgency of displayed information, and improves secondary task performance in judging distances and reacting on highlighted objects. As industry and research put a lot of effort in realizing highly automated driving, we considered this driving mode for 3D applications as well. If the car takes over the driving task, the driver is allowed to fully draw their attention to another activity. In accordance, we evaluated the impact of interacting with a 3D interface on the driver's take-over behavior if the system needs to hand over the driving task to the driver. Our findings prove that interacting in 3D space positively impacts the take-over quality of the driver in comparison to an interaction in two dimensions.

1.7 Thesis Outline

Overall, this thesis consists of eleven chapters which are separated into six parts. The *Background* (Part II) provides a fundamental introduction to stereoscopic 3D and automotive UIs. The body of this thesis is separated in three parts. First, the *Design Principles* (Part III) focus on the appropriate use of stereoscopic parameters in order to generate usable and comfortable 3D interfaces. Second, the *Prototyping Tools* (Part IV) tackle the challenge of developing 3D depth layouts and, therefore, apply the prior defined design principles. The *Automotive Application Domain* (Part V) presents S3D IC prototypes, developed by observing the defined design principles and applying our prototyping tools, and reports on the installation and evaluation of interactive 3D displays in the car. Related work is located in the *Background* and in the appropriate chapters of the main parts (Chapter 4 – Chapter 10). Finally, the *Conclusion* (Part VI) summarizes the research contributions of this thesis and provides interesting starting points for future work. Figure 1.2 depicts a visual outline of the thesis.

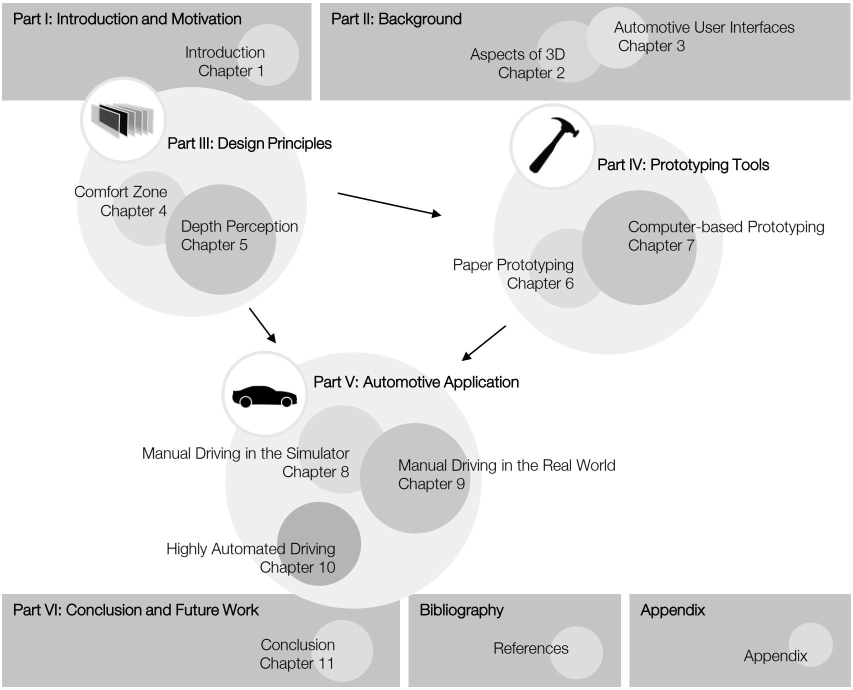

Figure 1.2: Thesis Outline.

Part II: Background

Chapter 2 – Aspects of 3D: This chapter provides an introduction to S3D. We describe the physiological and psychological fundamentals of the human visual system and the human depth perception. In this context, we introduce the general concept of stereoscopic presentations and discuss the difference of naturally and artificially presented depth. This is followed by an overview of 3D display technologies as well as their pros and cons. The chapter concludes with outlining opportunities and challenges in regard to the use of S3D to design a GUI. Therefore, we describe human factors related to spatial presentations and how various application areas profit from stereoscopy.

Chapter 3 – Automotive User Interfaces: The advent of highly automated driving requires the field of automotive UIs to be considered from two major perspectives. First, we focus on the traditional research area of automotive

UIs: driver distraction. As driver distraction is a well established research area, this chapter outlines the aspects of the driving task and the in-car design space, information processing theories, design guidelines, and evaluation standards. In addition, we report on the classification of automation modes ranging from manual to fully automated driving. Based on this classification we highlight the changing requirements on the in-car interface and particularly the contrast between manual and highly automated driving.

Part III: Design Principles

Chapter 4 – Comfort Zone: 3D displays are known to induce headache and nausea. One major reason is extreme depth positions of content elements in relation to the screen plane. We report on literature that recommends concrete limits of a depth range for a comfortable 3D experience. As recommendations in literature show high variances we conducted two laboratory studies with the aim of identifying proper comfort zone limits for an automotive IC and HUD. Although the comfort zone strongly depends on the viewer, we present a methodology that significantly reduces interindividual differences.

Chapter 5 – Depth Perception: We envision the layering of UI elements in space as a major advantage of 3D displays. A quick perception of the depth layout is crucial for structuring the UI in space in a beneficial way. We report on three laboratory studies with a display setup comparable to an automotive IC. The outcomes allow us to derive several design principles for successfully structuring elements in 3D. Moreover, we evaluate the ability of judging the position of real world objects with virtual elements displayed by a 3D see-through display. The results show that the augmentation of the real world through a 3D HUD allows the user to precisely estimate depth relations between virtual and real world objects.

Part IV: Prototyping Tools

Chapter 6 – Paper Prototyping: Paper prototyping enables the quick creation of UI variants in an early stage of the development process. As traditional paper prototyping does not directly support the exploration of spatial 3D layouts, this chapter presents a solution to overcome this challenge. It introduces two tools, the FrameBox and the MirrorBox, for paper prototyping

3D depth layouts. We present the design and development of the tools as well as their evaluation in two hands-on workshop sessions. In these workshops, UI designers used both tools as well as traditional paper prototyping. Their feedback reveals that especially the FrameBox overcomes the flat nature of paper and fosters creativity of using 3D space. In contrast, the MirrorBox is rated as cumbersome for paper prototyping but seems interesting for computer-based prototyping.

Chapter 7 – Computer-based Prototyping: Since the participants of the workshops, using the 3D paper prototyping tools, desired computer-based techniques to come up with spatial interface ideas, we developed two tools: the S3D-UI Designer and the S3D-HUD Designer. The tools allow prototyping digital 3D layouts. We developed both tools in an iterative process and evaluated the final systems in two separate user studies. The focus of the evaluation of the S3D-UI Designer is its collaborative use. We found that interacting with a touch surface fosters collaboration while a traditional desktop environment offers a better usability. The S3D-HUD Designer supports user input through mid-air gestures as well as mouse and keyboard. A laboratory study reveals that mouse and keyboard outperforms gesture interaction, while a further improvement of the gesture input might be promising.

Part V: Automotive Application

Chapter 8 – Manual Driving in the Simulator: Using 3D displays in cars is a potential factor of increasing the driver's distraction from the primary driving task. We developed a well-considered 3D interface for an IC by applying the formulated design principles as well as the prototyping tools. We compared a 2D with a 3D version of the IC in the driving simulator. Moreover, the participants explored the 3D effect while driving with two different display technologies. Our results reveal that the 3D effect does not negatively influence the primary driving task but improves secondary task performance. Thereby, it supports distance judgments and shortens reaction times on suddenly displayed content elements. However, these advantages depend on the use of a proper display technology which enables a high quality 3D effect.

Chapter 9 – Manual Driving in the Real World: The prior simulator study proved the applicability of 3D while driving. To study effects of interacting with a 3D display while driving through a real spatial environment, we equipped a vehicle with a 3D display as IC. With this experimental car we conducted an heuristic evaluation with experts in automotive UIs and a further user study with non-experts on real roads. The focus of both studies lies on a qualitative evaluation of the 3D effect and its applicability for automotive use cases. Although the used display technology needs further improvement, the experts as well as the non-experts highly appreciated the 3D effect. Beside its fascinating character, it supports elements that show a spatial analogy to the driving scene, as navigation cues, and helps in prioritizing the displayed content.

Chapter 10 – Highly Automated Driving: During highly automated driving, the vehicle takes care of the driving task. The driver can direct the full attention towards a non-driving related task. If the system can not handle the driving situation anymore it notifies the driver to take over the driving task. We investigated this particular situation in the driving simulator. The participants played either a 2D or 3D version of a game before an unexpected take-over request occurred. The outcomes of the study reveal that the interaction with the 3D display does not have a significant influence on take-over times but significantly improves the driver's take-over behavior.

Part V: Conclusion

Chapter 11 – Conclusion: In the conclusion, we provide a detailed summary about the research contributions of this thesis. Further, we point out and discuss potential areas of future work.

II

BACKGROUND

Chapter 2

Aspects of 3D

> *"The first effect of looking at a good photograph through the stereoscope is a surprise such as no painting ever produced. The mind feels its way into the very depth of the picture."*
>
> – **Oliver Wendell Holmes** (1859) [267]

1859 the famous American poet, Oliver Wendell Holmes, described the mysterious pleasure of perceiving a solid three-dimensional impression from a photography. The technique of creating such an illusion of depth is called stereoscopy. This chapter provides fundamental information about the human depth perception of real as well as stereoscopic 3D (S3D) stimuli in order to understand the complex construct of stereoscopy. Moreover, we give an overview on 3D display technologies with their advantages and disadvantages and discuss opportunities and challenges of using S3D for enhancing the human-machine interface.

2.1 Human Perception

In general, perception processes sensory information from external stimuli, such as smell, sound, sight, touch and taste, in order to interpret the environment [71, 227]. The perception of depth enables a 3D representation of our spatial surrounding in our brains. It is necessary to estimate distances in order to fulfill simple actions such as grasping a pencil, pouring water in a glass, or walking around a corner. A correct internal 3D representation is based on several cues which are of visual, tactile, and auditive nature. As the focus of this thesis is on visual displays, we exclusively discuss depth perception based on vision. For this reason, we give a short introduction to visual perception before we elucidate the difference of depth perception in real and virtual environments.

2.1.1 Vision

Objects in the surrounding reflect light that directly enters the eyes. The light is focused on the retina by the eyes' lens and cornea [71]. Cone cells (responsible for color vision) and rod cells (responsible for perceiving contrasts) on the retina translate the light into an electrical signal and transmit the visual information via the optical nerve to the brain. Due to the distribution of both photoreceptor cells there are three different visual areas [223]: foveal, parafoveal and peripheral vision. Foveal vision (visual angle: 1-2°) defines the area with the highest visual acuity[7] of the visual field (horizontal: 180°; vertical: 130°) and is located in its center. The area between 2° and 10° describes the parafoveal vision and the area beyond 10° is called peripheral vision. Impressions in the peripheral vision are poorly recognized. However, there are some cues, for example motion, which are still available. Binocular vision, being essential for depth perception, applies to viewing angles up to ca. 60° and hence is also present in peripheral vision.

2.1.2 Natural Depth Perception

There are multiple visual cues enabling spatial vision. Those can be classified in three main categories [62]: Oculomotor, monocular, and binocular cues.

Oculomotor Cues

There are two oculomotor cues communicating depth by muscular tensions in the eyes [62, 71]. *Convergence* results from the motion of the eye balls in order to focus on an object. For example, looking at a farther object and than focusing a nearby object requires an inward rotation of the eyes. *Accommodation* changes the shape of the lens in order to bring the target into sharp focus. For example,

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[7] Visual acuity is the ability to see details and can be measured, e.g., with a Snellen test [71, 220]. Normal visual acuity requires to resolve differences of 1 arc-min.

looking at a closer object than before requires the thickening of the lens. Both cues are perceived by contractions of the eyes' muscles and are closely linked [129].

Monocular Cues

Monocular cues just require the use of a single eye to extract depth information but are readily available using both eyes [62, 71]. The observer gained these cues from past experiences [40]. Monocular cues are extensively used for paintings as well as computer graphics to provide a spatial impression on 2D screens. In the following, we provide a short overview of the different monocular cues [71].

Relative size: The knowledge about the actual size of an object allows the observer to interpret its retinal image size. For example, if two spheres have the same size and different depth locations the foremost sphere appears bigger on the retinal image.

Height in the visual field: Objects positioned higher in the visual field seem to be farer away than objects beneath. This effect increases if a reference point such as the horizon is visible.

Texture gradient: Textures on surfaces get smaller and distort with increasing distance. Particularly, textures on the ceiling and the ground provide a rich feeling of space.

Linear Perspective: Parallel lines seem to converge in the distant. This effect also contributes to texture gradients.

Aerial Perspective: Small scattered water particles in the air vanish colors, shapes and contours in the distant. This effect strongly depends on the atmospheric humidity.

Occlusion: If one object occludes another, it appears closer than the occluded one. Occlusion is one of the strongest depth cues.

Lighting effects: Shadows, specular reflections, and brighter illumination are very powerful for communicating depth. For this reason, the optimal positioning of lights in the scene is a key for an impressive spatial effect.

Motion Parallax: Motion strongly conveys depth in dynamic scenes. Object occlusions change and farther objects seem to move slower than nearby objects. Motion can occur due to the movement of the observer or the objects in the visual field. The term motion perspective refers to the relative motion of stationary objects which results from a moving observer.

Binocular Cues

In contrast to monocular cues, binocular cues require the vision of both eyes [71]. The eyes of the average adult are horizontally separated by 63 mm [53]. As a result, the left and right eye perceive slightly different images of the world. The difference between the two images is called *binocular disparity* or *retinal disparity* [177]. *Stereopsis* defines the depth perception based on binocular disparity.

The fixation of an object stimulates corresponding points on the retinas of the left and right eye [71, 177]. The *horopter* defines an arc that passes through the fixation point. All objects located on the horopter address corresponding retinal points and hold zero binocular disparity. Objects which are not positioned on the horopter stimulate non-corresponding points and exhibit binocular disparities which increase with the objects' distance from the horopter. Objects in front of the horopter result in crossed disparities since the eyes need to cross for a fixation. In contrast, objects behind the horopter induce uncrossed disparities. In summary, the horopter is a baseline depth plane aligned through the point of fixation and allows the judgment of other depth planes.

Around the horopter, there is a zone called *Panum's fusional area* [129, 177]. The retinal images of the objects that fall into this area are perceptually fused and seen as single stereoscopic objects. In contrast, objects located outside Panum's fusional area are seen as double images, diplopia occurs. The size of Panum's area varies along the horopter. For foveal vision sensory fusion is limited to a binocular disparity of 10 arc-min, at an eccentricity of 6° (parafoveal vision) fusion limits are 20 arc-min, and at 12° (peripheral vision) images can be fused up to 40 arc-min binocular disparity.

The term *depth of focus* describes a range around the retina in which objects are seen in sharp focus without adjusting the eyes' accommodation [129, 262]. It is measured in diopter (i.e., m^{-1}). Outside this area the images are perceived blurry. In this way, excessive binocular disparities are accompanied by blurred vision. This contributes to suppress the conscious perception of double images. The limits of depth of focus is influenced by various parameters, for example, pupil size and object contrast. Typical values range from 0.2 to 0.5 diopter.

Stereoacuity defines the smallest detectable depth difference due to binocular disparity [49, 177]. There are high variances between individuals. But stereoacuity is a superacuity [246] and the average value of 20 arc-sec emphasizes the human precision in detecting small differences in S3D depth [177]. Coutant and Westheimer [42] conducted a study on stereo acuity with 183 participants. Their

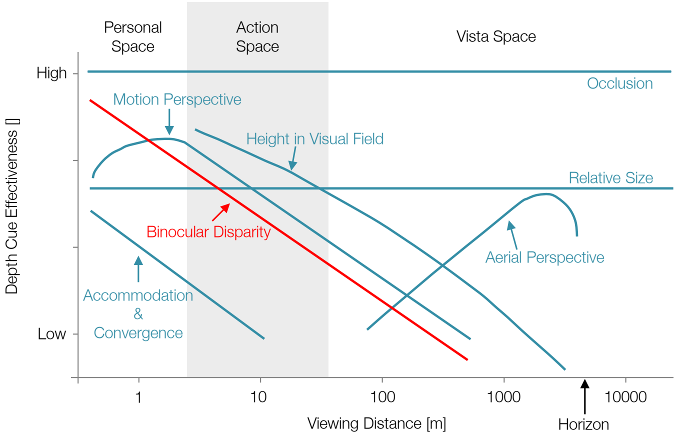


Figure 2.1: The effectiveness of depth cues depend on the viewing distance. The diagramm is based on just-discriminable ordinal depth thresholds as a function of the logarithm of the viewing distance following Cutting and Vishton [45]. Binocular disparity is most effective at near distances.

results showed that 97.3% were able to identify depth differences of 2.3 arc-min or less and 80% detected differences of 30 arc-sec.

Cue Integration and Efficiency

So far, we described a number of different depth cues. In most situations several cues are present at the same time. The human brain has to integrate the given information in order to come to a proper assumption of the depth layout [62]. There is evidence that the visual system combines depth cue information in an additive manner [30]. The redundancy decreases the probability of misjudgments. In the case of a failure of one single cue, there are still other sources communicating the correct depth information. The human brain processes cue information by weights based on cue reliability and consistency. The weight of single cues varies due to the environmental context and physiological state of the observer. In particular, the effectiveness of different depth cues changes along the viewing distance. Cutting and Vishton illustrated this relation as Figure 2.1 shows [45]. They divide the viewing distance into three classes:

Personal Space: This space defines distances up to 1.5 meters from the observer and, hence, is quite personal. Typically, the observer is stationary when working in this space. Effective cues are occlusion, binocular disparity, relative size, convergence, and accommodation. If several of these cues are available, they dominate each other in that order. In regard to the automotive domain, the whole cockpit with its screens, except the HUD, lies in the personal space of the driver.

Action Space: Beyond personal space, action space ranges up to 30 meters from the observer. There, the public action of individuals takes place. Persons can move quickly within this space and interact with others. Effective cues are occlusion, height in the visual field, binocular disparity, motion perspective, and relative size. In the car, the focal plane of the HUD typically falls in the action space.

Vista Space: Beyond 30 meters there are very little changes for the observer since motion of objects is less salient and binocular depth perception is diminished. In the vista space, only static monocular cues are efficient: occlusion, height in the visual field, relative size, and aerial perspective. Vista space plays a major role for the primary driving task especially at higher speed.

2.1.3 Virtual Depth Perception

Information displays can provide three dimensional presentations by exploiting the knowledge about human depth perception. High performance graphic cards allow the real time rendering of complex virtual 3D scenes and the integration of monocular depth cues, such as lighting effects, linear and aerial perspective. Moreover, there are display technologies which support the perception of binocular depth cues. Stereoscopy describes the technique of creating a binocular depth impression on a planar surface. It provides two different images to the viewer, one for the viewer's right eye and one for the left eye. Slight horizontal differences between the left and right eye picture enable a solid 3D impression. In the following, we discuss depth perception based on stereoscopic display devices.

Geometric Model

The geometric model of depth perception induced by a stereoscopic display device is well studied [49,93,95,114]. In the following, we describe a simplified geometric model emphasizing the key variables of perceiving S3D content.

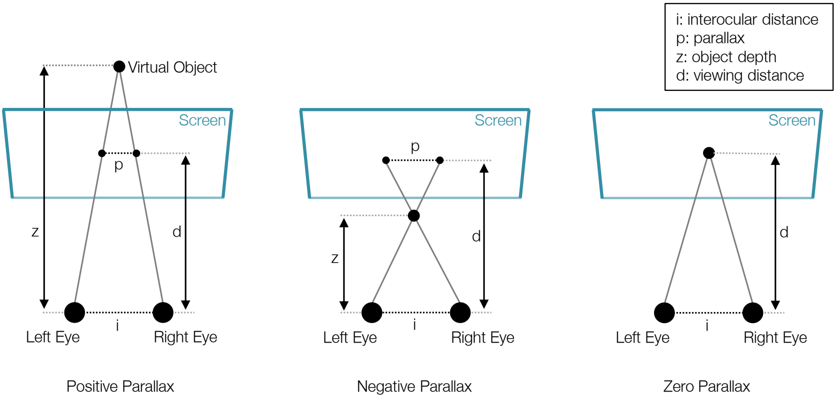


Figure 2.2: The screen parallax defines the depth of the virtual object.

Figure 2.2 shows a schematic illustration of a viewer's eyes with an interocular distance i looking at a 3D display with a viewing distance d. The 3D screen shows slightly different horizontal positions of an object for the viewer's left and right eye. This horizontal difference is called screen parallax (p) or screen disparity [93,95]. The parallax depends on the perceived depth z of the displayed object, the viewing distance, and the interocular distance:

$$p = i(1 - \frac{d}{z}) \tag{2.1}$$

Positive Parallax ($p > 0$), also called positive or crossed disparity, describes depth positions of virtual objects perceived behind the screen plane ($d < z$).

Negative Parallax ($p < 0$), also called negative or uncrossed disparity, defines depth positions in front of the screen ($d > z$).

Zero Parallax ($p = 0$) does not reveal a difference between the left and right eye image. As a result, the image appears at screen depth.

Using equation 2.1, we can calculate the perceived depth from the displayed parallax as follows:

$$z = \frac{di}{i - p} \tag{2.2}$$

The presented geometric model allows us to draw several facts about viewing S3D images:

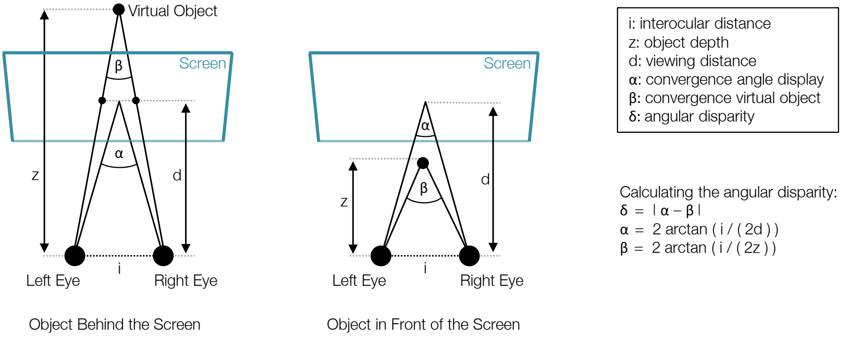


Figure 2.3: The convergence angles α and β define the angular disparity δ.

- Increasing the absolute parallax ($|p|$) results in a greater perceived distance ($|z-d|$) to the front of or behind the screen surface. A parallax equal to the interocular distance results in the perception of the object at infinity:

  $$z = \lim_{p \to i} \frac{di}{i-p} = \infty \tag{2.3}$$

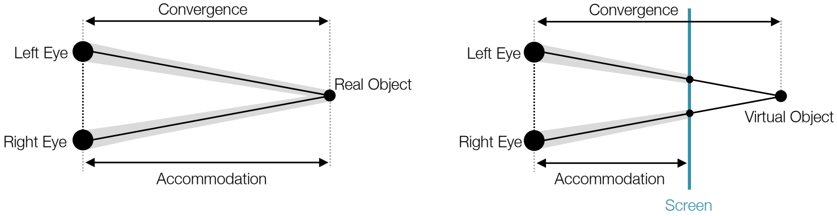
  If screen parallaxes are greater than the viewer's interocular distance the optical axes of the eyes have to diverge to perceive the corresponding images. As this divergence does not take place of viewing real spatial layouts, it is strongly recommended to avoid screen parallaxes which force this unnatural posture of the eyes [140, 153].

- A variation of the viewing distance affects the perceived virtual depth. For instance, increasing the viewing distance results in larger depth ranges between the virtual object and the screen plane.

- The interocular distance of the viewer also impacts the depth impression. For example, a child with a small interocular distance perceives for the same S3D image greater depth ranges as an adult.

We can express screen parallax in meters or pixels (depending on the pixel pitch of the used display) [153]. Besides, depth ranges are often specified in angles [66, 184, 214]. Figure 2.3 depicts the parameters for calculating the angular disparity δ:

$$\delta = |\alpha - \beta| = |2 * arctan(\frac{i}{2d}) - 2 * arctan(\frac{i}{2z})| \tag{2.4}$$



(a) Natural Depth Perception (b) Virtual Depth Perception

Figure 2.4: Viewing S3D layouts cause a conflict of the oculomotor cues, accommodation and convergence.

Accommodation-Convergence Mismatch

There is one major difference between depth perception in the real world and a S3D presentation. For natural layouts, the eyes have to accommodate and converge at the same distance. For S3D layouts, there is a conflict between convergence and accommodation [94, 129, 215]. The eyes have to accommodate on the screen surface, showing the sharp left and right eye picture, while they converge on the position defined by the screen parallax (cf., Figure 2.4). The mismatch between accommodation and convergence is a significant reason for visual discomfort and fatigue when viewing S3D content. As the conflict between the cues grow for increasing object distances from the screen layer it is advisable to avoid excessive positive and negative parallaxes. Lambooji et al. [129] recommend object positions within the eyes' depth of focus, which defines the area of sharp vision without adjusting the accommodation. Please refer to Appendix I for the geometric relation between depth of focus and angular disparity limits.

Random Dot Stereogram

Julesz [116] showed that S3D images communicate depth without presenting any depth information other than binocular disparity. Random-Dot Stereograms (RDSs) are random dot patterns presented to the left and right eye of the viewer. The two patterns have a screen parallax in form of a certain shape. The viewer can solely see the depth layout of this shape by using a stereoscopic display device and being able to perceive screen disparities. Stereo blindness affect ca. 5-10 % of the population and occurs due to strong asymmetric visual acuities, problems in converging the eyes such as strabismus, or the loss of vision in one eye [129, 153]. RDSs can be used to test the viewer's ability in stereo vision [231]. Appendix II provides examples for RDSs.

2.2 3D Display Technology

3D displays enable the use of binocular cues. There are several technologies which we classify in three categories: glasses-based displays, autostereoscopic displays, and real 3D displays. In this section, we give an overview of the most prominent approaches based on the presented classification. Detailed information about 3D display technology can be found in further literature [144, 238].

2.2.1 Glasses-based Displays

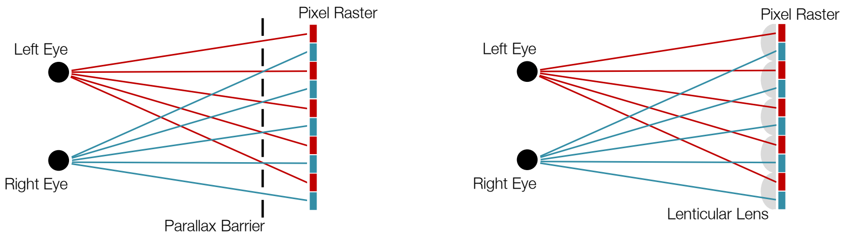
Stereoscopic displays provide two different images for the viewer's left and right eye in order to generate a 3D effect. The two images are encoded on a 2D screen and a decoding mechanism caters for the presentation of the images in the respective eye. There are several display technologies using special glasses for separating the two image channels.

Anaglyph images use complementary colors for encoding and decoding the left and right eye channel [153, 261]. Commonly the colors red and cyan are used for encoding the left (red) and right eye image (cyan). Wearing anaglyph glasses the complementary colors are filtered for each eye. In this way, the left eye solely perceives the red images while the cyan image passes the filter of the right eye. Anaglyph stereo is simple and inexpensive in production but exhibits a rather low image quality. It can not support the whole color spectrum and lacks in a clear separation of the two image channels.

Interference Filter use different wave lengths of the color for the left and right eye image [115, 144]. Only specific wave lengths pass the required glasses for the left and right eye. The image separation of this approach is very precise and allows the presentation of the whole color spectrum.

Polarization requires to split up the display's resolution [144]. One half depicts the right eye image and the other half the left eye image. The left and right eye pictures are vertically interlaced, alternating one row of the left and one row of the right image. The light of the right and left eye image are differently polarized using either linear (perpendicular) or circular polarizations (left- or right-handed). The lenses of the glasses filter the polarized light and, hence, the viewer's left and right eye perceive the appropriate images.

Shutter displays alternately show the left and right eye image on the display [144]. The viewer has to wear liquid crystal shutter glasses which are synchronized with



(a) Parallax Barrier (b) Lenticular Lens

Figure 2.5: There are two approaches for enabling autostereoscopic displays which allow for perceiving a S3D effect without glasses.

the display. The glasses switch the right eye lens to transparent and darken the left eye lens if the display shows the right eye image and vice versa. This enconding and decoding principle is based on time and the viewer does not perceive both images simultaneously. This requires high frame rates, usually 120 Hz [238]. Although this technology provides full resolution and full color 3D the alternating opacity of the shutter glasses reduce the brightness of the image. Nevertheless, shutter achieves a very high and pleasing 3D quality [17].

A **Head-Mounted Display (HMD)** requires the user to wear the display on the head [17, 96, 176, 187]. Binocular HMDs directly place the 3D image in front of the user's eyes using two micro displays with optical elements. Blocking the natural environment acoustically and visually enables a full immersive virtual experience. In contrast, binocular see-through HMDs can augment the real 3D world with virtual objects [229].

2.2.2 Autostereoscopic Displays

Autostereoscopic displays allow for experiencing stereoscopic images without any kind of special glasses or user-mounted devices [54, 96, 144, 238]. There are two types of autostereosopic displays: two-view displays and multiview displays. Two-view displays provide only one single stereo pair while multiview displays produce multiple stereo views. Parallax barriers or a lenticular lens array enable both display types (cf., Figure 2.5). In the following, we introduce barrier and lenticular displays for two view systems. Please refer to the work of Dogdson [52, 54] for further information about the generation of the viewing zones in multiview displays.

Parallax Barrier: The display presents the left and right eye image simultaneously by interlacing both images. In front of the pixel raster a barrier mask is placed occluding half of the display's resolution from the left eye and half from the right eye (cf., Figure 2.5(a)). The viewer perceives the correct S3D image at a central position in front of the display, called sweet-spot or eye box. The optimum viewing distance depends on the pixel size as well as the distance between the display and barrier layer. Because of the barrier mask the brightness of the resulting S3D image is reduced [238].

Lenticular Lens: In accordance to parallax barrier systems the display shows an interlaced image of a stereo pair but uses refraction instead of occlusion for directing the light of the images into different viewing windows. The refraction occurs due to an array of cylindrical lenslets placed in front of the pixel raster. If the viewer has a certain viewing angle, the S3D effect is visible. In fact, lenticular lenses generate brighter images than barrier systems. But the alignment of the lens array is critical and any misalignment can cause image distortions [134].

For both approaches, parallax barriers and lenticular lenses, the user solely perceives a proper S3D effect in defined positions in front of the display. Even slight movements impair the S3D impression as the left eye sees parts of the right eye image and vice versa. Tracking the viewer's head, or more accurately the eyes, allows the adaption of the display's sweet spot due to their position. However, most tracking solutions are single viewer systems. For multiuser purposes, multiview displays are a possible solution.

2.2.3 Problems of Stereoscopic Displays

There are several stereoscopic distortions that rise from image generation as well as the used display technology [129, 150, 260]. Visual discomfort and fatigue on the part of the viewer occur due to these distortions.

Image-Related Distortions

Image-related distortions are the result of improperly capturing the left and right eye image of a 3D scene (real or virtual). In accordance to the human perception of S3D images (cf., Subsection 2.1.3), the S3D content creator has to consider the camera configuration (i.e., toed-in or parallel), the interaxial value defining the distance between left and right image camera, the cameras' field of view, the convergence value (i.e., distance to object with zero parallax), as well as the used depth budget (i.e., parallaxes presented on the display) [114, 153, 260].

Excessive Screen Parallaxes: High parallax values increase the conflict between accommodation and convergence resulting in uncomfortable viewing experiences. If the parallaxes exceed a certain limit the human visual system even fails in fusing the two images and diplopia occurs [129, 265]. The limits of fusion for S3D displays depend on many factors such as exposure duration, luminance, stimulus size, and individual aspects.

Keystone Distortion and Depth Plane Curvature: Keystone distortions result from a toed-in camera setup [260]. The left camera image provides a larger left and smaller right side than the right camera image. This results in incorrect vertical and horizontal parallaxes which are greatest in the corners of the image. The viewer perceives a curvature of the depth planes. Objects located at outer horizontal positions appear to be further away than objects centered in the image. The distortion decreases for a lower interaxial distance and a higher convergence value. A parallel camera configuration completely eliminates this effect.

Window Violation: If an object appears in front of the screen and is cut off by the screen's frame as it leaves the display surface, a stereoscopic window violation occurs [153, 246]. The occlusion reveals that the frame must be in front of the virtual object but the negative parallax suggests that the object is placed in front of the screen and its frame. In general, the resulting conflict between these strong depth cues should be avoided. In cinematography the integration of a floating window solves the cue conflict. A black mask builds a virtual frame placed in front of the object. As the audience generally does not notice the rather small black stripes, the usage of this technique is highly recommended for 3D cinema.

Puppet Theater Effect: The puppet theater effect makes objects look tiny [232]. In particular, people appear unnaturally small as puppets. A relatively high interocular distance can cause this effect.

Cardboard Effect: 3D objects appear flat and not solid. This effect occurs due to the settings of the camera lenses focal length, interocular distance, and convergence. The object's disparity is too small in relation to its depicted size.

Display-Related Distortions

Display-related distortions are caused by the used display technology. In general, autostereoscopic displays unfold more problems than glasses-based technologies.

Crosstalk: Crosstalk is one main issue of 3D image quality and visual discomfort [129]. It corresponds to the imperfect separation of the left and right eye image channel. The viewer perceives crosstalk as ghosting images, shadows, and double contours. The visibility of these effects increases with increasing screen parallax as well as contrast of the S3D image [175].

Shear Distortion: Most stereoscopic display technologies present just one point of view of the depicted scene. If the viewer moves, the S3D image seems to follow this movement [260]. Objects in front of the display shear in the moving direction of the viewer while objects with positive parallaxes move in the opposite direction. The dynamic appearance increases for objects with higher parallaxes. Adjusting the perspective of the stereo pair by tracking the viewer's head position can avoid shear distortions [114, 150].

Picket Fence Effect and Image Flipping: The picket fence effect and image flipping are typical artifacts of autostereoscopic displays [129, 150]. If the viewer perceives vertical stripes in the image, the picket fence effect occurs. In general, a lateral movement of the viewer's head evokes this effect since the vertical banding is more visible from certain angles. Image flipping also appears during lateral movements and refers to the noticeable transition between the multiple viewing zones. Tracking the user's position can reduce both artifacts.

2.2.4 Real 3D Displays

Real 3D display technologies overcome the typical problems of stereoscopic viewing devices by producing true 3D imagery. Volumetric displays consist of a volume in which spatial points, called voxels, can be controlled to generate 3D images [15, 64, 113]. In contrast, holography first records the complete wave field of an object and then reproduces this indistinguishable from the original image with all optical properties such as its three dimensional appearance [38]. Nevertheless, more research and development is needed before volumetric and holographic technologies find their way in commercial products [96, 238]. In contrast, multi-layer displays (MLDs), which consist of two or more display layers, have been developed and commercialized [8, 11]. Typically two flat LCD panels are stacked in depth with a defined distance. This display concept overcomes conflicting cue problems of (auto)stereoscopic displays but restricts the 3D design space to a limited number of layers.

For our research, we focus on the use of (auto)stereo technologies as they offer an interesting design space. Hence, the use of depth is not limited to fixed depth positions but is challenging due to S3D artifacts. Particularly, in-car displays require glasses-free solutions. We also applied shutter displays in our studies as we assume their high 3D quality as benchmark for future autostereo displays.

2.3 Stereoscopic User Interfaces

We envision S3D visualizations for enhancing the UI. The previous sections show that there are some issues for properly displaying S3D content. In this section, we discuss potentials and challenges of stereoscopy for designing the UI by reviewing its application in various domains. Previous research reveals positive as well as crucial aspects about the use of stereoscopy. We identified three aspects recommending its use. Beside its fascinating character contributing to hedonistic aspects of user experience, it shows its utilitarian value for structuring information and interacting with spatial elements. However, there is one issue which comes along with S3D presentations, namely visual discomfort and fatigue.

2.3.1 User Experience

User experience addresses the feelings and experiences of the user while interacting with a system [91, 132]. Hence, user experience is a subjective construct and encompasses a variety of aspects ranging from usability over aesthetics to the hedonistic, affective use of an interactive system. As S3D images support binocular depth cues they can provide a more natural viewing experience [213]. Freeman and Avons [65] conducted a study comparing TV sequences in 2D against S3D. The results show that S3D increases presence[8] as participants described sensations attributing to involvement, realism, and naturalness. Häkkinen et al. found similar results [82]. Beside an increased feeling of presence they showed that stereoscopy enhanced emotions conveyed by short video clips. The relationship between the sensation of presence and stereoscopy is not limited to the domain of 3D movies [103, 104] but also affects eye-catching advertising on public displays [47] and gaming experience [206]. However, Mahoney et al. [146] emphasize that game developers should consider S3D from the very beginning of the development process for successfully enhancing the users' immersion. For mobile phone applications stereoscopy outperforms its 2D counterpart due to its hedonic quality, as well [80, 228]. Thereby, typical positive attributes related to the S3D UI are "visually pleasant", "entertaining", "exciting", "innovative", and "empowering". However, the 2D version of the interface earns attributes related to pragmatic quality such as "clear", "familiar", "simple". Nevertheless, Häkkila et al. [81] demonstrates the pragmatic and hedonic quality of a S3D mobile phonebook application. They use the 3D effect for communicating the

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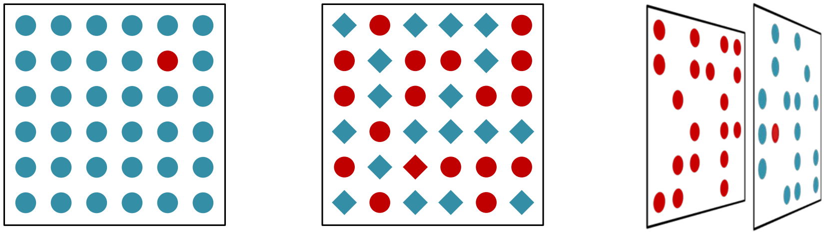
[8] Presence describes the sensation of "being there" in a mediated environment [65].



(a) Find the red circle (b) Find the red diamond (c) Find the red circle in front

Figure 2.6: Visual search based on one feature as color (a) is parallel. The conjunction of color and shape (b) leads to a serial search. If one feature in a conjunction is stereoscopy (c) the depth planes can be searched in parallel (redrawn from [162, 179].

time since the persons of a contact list have been last called. A field test shows that the gain in pragmatic as well as hedonic quality due to stereoscopy is still significant after using the S3D application for two to three days. Regarding the use of depth cues, Mikkola et al. [156] compared images incorporating different cues such as as shadows, texture gradient, focal blur, and S3D. Their study reveals that S3D gathers significantly higher image quality and acceptance ratings in contrast to the tested monoscopic cues. In summary, stereoscopy can contribute to the design of a more natural, immersive, and compelling UI.

2.3.2 Information Structure

Beside hedonic aspects, stereoscopy can improve the user performance in certain tasks. McIntire et al. [149] reviewed 71 experiments comparing the user performance using a 2D versus a 3D display. One finding of their literature review is that a S3D effect can help in finding, identifying, or classifying objects.

Visual search requires the localization of a target among a set of distractors. The *feature integration theory* of Treisman [62, 71, 235] describes that the search is parallel if the target literally "pops-out" from the distractors. This means, the target can be identified instantly based on a single salient feature (e.g., color, shape, motion, size), regardless from the number of distractors. Figure 2.6 (a) exemplifies parallel search based on color with a red circle as target. If the target is defined by a conjunction of two or more features, for example by color and shape as shown in Figure 2.6 (b), a serial search occurs. Search time increases with the size of distractors as finding the target requires focused attention. Nakayama and Silverman [162] found that stereoscopy plays a particular role in visual search. The conjunction of binocular disparity with another feature, for example color or motion, can be searched in parallel. Figure 2.6 (c) illustrates the conjunction of binocular disparity and color. The target, which is the red object in the front layer, is found immediately as a parallel search can occur on the layer in front. Hence, the search time is independent of the number of distractors. Dünser et al. [57] found similar effects using a MLD with two layers. They used a more complex search task and showed that putting the target on the front layer and the distractors on the back layer significantly improves search performance. The conjunction of stereoscopy and color for highlighting information is successfully demonstrated for graph visualizations [4] and thumbnail lists of mobile devices [102].

The concept of *layered user interfaces*, introduced by Harrison et al. [85], shows the benefits of binocular disparity for information segregation and visual clutter management [180, 197, 257]. For example, a study of Parrish et al. [197] reveals that stereoscopy improves the user performance in a simulated tracking task on a visually cluttered flight display. Added visual noise cluttered the display. Separating the visual noise, tracking, and target symbol on three distinct depth layers reduced the impact of visual clutter and supported the users in identifying the tracking and target object. In addition, Wong et al. [257] explicitly recommend to present the information the user has to attend to on a front depth layer while placing secondary information on a rear depth layer. According to Mizobuchi et al. [159], the layer of primary interest should have zero parallax.

There are several studies investigating the visual attention in S3D static and motion pictures [7, 13, 160, 183]. Atchley et al. [7] show that the cost of switching the attention between depth planes is higher than switching attention on a 2D plane, proving a depth aware attentional spot-light. However, this effect is only present if perceptual load in the form of visual distractors is present. In general, switching visual attention between two layers occurs faster for converging eye movements (changing convergence from the back to the front) than for diverging eye movements (changing convergence from a depth layer in the front to a backward layer) [160]. Using an object that continuously ranges from the forward to the backward layer decreases the time required for an attention transition between depth layers [183].

The findings of former studies provide evidence that structuring information on different depth layers supports users in managing their attention. A well considered depth arrangement allows focusing attention on a single UI object as well as dividing attention between multiple objects [85]. But how should the developer choose proper depth positions for UI objects? This thesis provides answers to this question with the ultimate goal to develop usable and compelling S3D applications.

2.3.3 Depth Perception and Spatial Understanding

The comprehensive review of McIntire et al. [149] shows that 3D displays can enhance user performance in tasks that require a spatial understanding. Such tasks include judging depth relations and a spatial manipulation of objects.

There are several tasks that allow measuring the user performance in judging absolute and relative depth [229]. Mikkola et al. [156] presented their participants a number of objects on different depth planes as well as a reference object. There was only one object, the target, that shared the same depth level as the reference object. Mikkola et al. used this task to compare various depth cues, namely texture gradient, shadows, focal depth, stereoscopy, and a combination of all cues. The results reveal that the conditions with stereoscopic cues outperformed images using monocular cues in terms of task completion time as well as error rate. Rosenberg [195] used another task for evaluating depth judgments. A positioning task required the participants to adjust the depth position of an object according to a reference object. His findings show that S3D significantly improves the accuracy in positioning. Van Beurden et al. [240] used a visual path tracing task that required the viewer to understand a complex depth layout of four lines randomly crossing each other in space. The goal was to identify the endpoint of one line which was marked at its lower end. Van Beurden et al. used this task in three levels of complexity in order to investigate task performance, and cognitive workload due to S3D. The findings reveal that S3D increases user performance (task completion time and accuracy), particularly for more complex tasks, and reduces workload for moderate screen parallaxes (i.e., 5-25 arc-min). In summary, S3D can improve the judgment of spatial relationships [9, 99, 101, 148, 239]. Particularly, its advantage fully unfolds for images in which monoscopic depth cues are degraded or scene and task complexity is high [149, 240, 265].

Hubona et al. [101] demonstrated that S3D improves user performance on positioning and resizing spheres in computer-generated spatial tasks. As stereoscopic displays support the understanding of spatial layouts they are often applied for a professional use, for example in medicine, military, and for visualizing scientific data. In particular, complex 3D layouts such as cave systems [186], 3D models for computer-aided design (CAD) systems [19], and anatomical structures in radiographic images [241] profit from a S3D visualization. Moreover, S3D provides a better user performance in teleoperating vehicles and robots [39, 56] and improves surgery time as well as accuracy in minimally invasive surgery [241]. In particular, the operator of a teleoperation system needs a clear understanding of the real world situation in which navigation or manipulation takes place. S3D can improve those tasks [39, 147]. Zocco et al. [266] successfully demonstrated the superiority of S3D against a monoscopic visualization for enhancing the situation awareness in a computational warfare system showing the geographic position of forces and entities. This exemplifies that S3D visualizations can comprehensibly communicate spatial and timely relationships of objects in real world situations.

2.3.4 Visual Discomfort and Fatigue

Although stereoscopic displays unfold great potentials for various applications there is one major shortcoming of this display technology. They are known for inducing visual discomfort and fatigue. Although literature often uses the terms visual discomfort and visual fatigue interchangeable they are basically two different but related constructs [129]. Visual fatigue defines the decline in performance of the visual system, which is objectively measurable whereas its subjective counterpart refers to visual discomfort. Visual fatigue leads to symptoms ranging from eyestrain, tired and sore eyes, feeling of pressure in the eyes over double and blurred vision, problems in changing the focus, reduced visual acuity and speed of perception to headaches, ache around the eyes, shoulder and neck pain and a decline in work efficiency and concentration [130].

Alternations in visual performance (e.g., accommodation and convergence responses, pupillary dynamics, visual and stereo acuity) indicate visual fatigue on the users' side [129]. The performance alterations can be directly measured using optometric instruments, for example refractometers and pupil trackers. Also, brain activity measures can be applied. Moreover, changes in visual performance can be measured indirectly using vision tests (e.g., a Snellen test [220]). Visual discomfort can be assessed by using explorative studies and questionnaires. Examples for explorative studies provide Freeman and Avons [65] using focus groups and Häkkinen et al. [82] applying the Interpretation Based Quality (IBQ) approach for comparing S3D with monoscopic video sequences. For the IBQ approach the participants reported their preference after watching a sequence in both conditions (2D and S3D) followed by an interview asking about reasons for the chosen display mode. As explorative approaches assess beside visual discomfort other aspects (e.g., presence), questionnaires allow for specifically assessing viewing comfort. Hoffmann et al. [94] proposed a questionnaire for measuring visual discomfort induced by 3D displays. The questionnaire consists of five items, rated on five-point scales, asking about typical symptoms such as headache and eye strain. There are also various studies which use the Simulator Sickness Questionnaire (SSQ) of Kennedy et al. [120] for evaluating visual discomfort induced by S3D [83, 156, 205, 206].

Reasons for visual discomfort and fatigue are accommodation-convergence (AC) mismatches (cf., Subsection 2.1.3) as well as distortions caused by the used display technology, the content creation and screen design (cf., Section 2.2.3). If the viewers suffer from uncomfortable S3D presentations, the aforementioned potentials become void or even turn to disadvantages [149]. Hoffman et al. [94] demonstrated that a real 3D display compared to a stereoscopic display reduces the time of identifying a 3D stimuli, decreases stereoacuity during time-limited tasks, and improves visual comfort. Their experiments clearly prove that the AC conflict caused the performance and comfort decline. Recommendations for lowering AC conflicts are (1) increasing viewing distances since the effectiveness of accommodation rapidly decreases with distance [44, 94, 248], (2) maximizing the availability and reliability of other depth cues as this might decrease the weight assigned to accommodation [94, 248] and (3) reducing screen parallaxes to an acceptable range [114, 129, 214]. Beside the AC mismatch, fast object motion also increases visual discomfort. Both, quick movements along the depth axis [225] as well as fast motion on one depth layer [137] lower the viewing comfort for S3D presentations.

2.4 Summary

This chapter provides an introduction to various aspects of 3D, ranging from the human visual perception over 3D display technology to potentials and challenges of S3D UIs. In general, S3D can contribute to a more natural perception of virtual content, improves the visual structure of information displays, and fosters the depth perception of spatial UI elements. Former studies prove its potential in various application domains such as entertainment, public displays, mobile devices, medicine, military, and avionics. However, all aspects of S3D, particularly the display technology, a proper depth layout, as well as possible S3D distortions, need to be considered from the beginning of the development. Otherwise, visual fatigue and discomfort can decrease both pragmatic as well as hedonic quality. This is particularly important for in-car applications as an increased visual load can hazardously distract drivers from their primary task, driving.

Chapter 3

Automotive User Interfaces

Automotive UIs approach a paradigm shift from manual to highly automated driving. While manual driving requires the driver to primarily attend to the driving task, highly automated driving allows them to draw their full attention to other tasks. In this chapter, we introduce both extremes of driving. While little knowledge exists about human factors and highly automated driving, there is an excessive amount of research about the interplay between the primary task of manual driving and a further secondary task, for example selecting a desired audio source or calling a contact. As a result, we give first an overview on established principles about automotive UIs intentionally applied for manual driving. Second, based on the well-established terminology for driver distraction we come up with a nomenclature for highly automated driving and review its characteristics and research challenges. Both steps allow us to derive research directions for the application of S3D in the context of automotive UIs.

3.1 Driver Distraction

Driving a car has fundamentally changed over the past years of automotive history. In its very beginning, solely the devices for steering, accelerating, and breaking were available in order to maneuver the vehicle to a certain destination. Although these devices have not fundamentally changed in the last 100 years, today various input and output devices in the car allow the driver to access beside vehicle data (e.g., speed, revolutions per minute (rpm), fuel level), multiple driver assistance and infotainment functions. Driving a modern car comprises the interaction with the navigation system, playing music from various sources (radio, digital music services such as Spotify[9], external device), and communication functions such as receiving and replying to e-mails, text messages, and telephone calls. Interacting with this complex function set while driving is one source for driver distraction [50, 164, 217].

As a result, the design of interactive systems for an in-car use is crucial and needs to satisfy standardized requirements and regulations in order to minimize driver distraction. In the following, we give an overview about established definitions, principles, and models related to the interaction between the driver and the vehicle. Please find a detailed description of this research area in [34, 117, 190].

3.1.1 Taxonomy of the Driving Task

An accepted description of the driving task represents the *3-Level-Model* of Donges [55, 258]. This hierarchical model divides the driving task into three subtasks:

Navigation: On the highest level, the navigation task comprises the choice of the route in order to reach a desired destination. Several issues influence the navigation task, for example, traffic density, accidents, construction sites as well as potential interim destinations. Today, navigation systems can support the driver in the navigation task.

Maneuvering: Based on the navigation level, the maneuvering task derives concrete driving maneuvers, for example, changing the lane, keeping the distance to the vehicle in front, or turning at a junction, from the chosen navigational route. This requires the driver to perceive and interpret the current traffic situation and then to decide on the appropriate driving speed and lane position. Today, advanced driver assistance systems such as Active Cruise Control (ACC)[10] can support the driver in the maneuvering task.

Stabilization: The lowest level defines the stabilization task. The driver uses the steering wheel as well as the pedalry in order to perform the maneuver derived by the maneuvering task. As a result, the driver is part of a closed control loop compensating deviations from the intended and actual course of the vehicle.

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[9] https://support.spotify.com/us/learn-more/faq/#!/article/bmw-integration/, last accessed September 12, 2015.

[10] ACC controls the speed due to a predefined value while keeping a certain distance to the vehicle ahead.

Figure 3.1: We can classify the vehicle controls in accordance with the primary, secondary, and tertiary task (based on [143, 233]).

All activities of the 3-Level-Model are part of the primary driving task [68]. Beside the primary driving task, the driver fulfills additional activities while driving, which can be classified in the secondary and tertiary driving task [31]. The controls of a vehicle can typically classified according to the primary, secondary, and tertiary task as Figure 3.1 shows. In the following, we describe the three classes of the driving task:

Primary Driving Task: The primary driving task refers to the specific process of moving the vehicle though the environment with the goal to avoid any physical contact with other static and moving objects. Allen et al. [2] divides the control over the vehicle in two subtasks namely the speed (longitudinal control) and steering control (lateral control). Longitudinal control defines the adjustment of the current speed such as accelerating and breaking whereas lateral control refers to actions which influence the horizontal position of the vehicle, for example, steering in order to keep the current lane.

Secondary Driving Task: To enhance road safety and driving performance, the secondary driving task addresses actions which arise due to traffic or environmental conditions. These actions include the operation of windscreen wipers and headlights as well as the interaction with other traffic participants (e.g., activating turn signals, hazard lights, or the horn).

Tertiary Driving Task: In contrast to primary and secondary tasks, tertiary tasks are not directly related to the driving task itself but satisfy the driver's need for comfort, entertainment, and information. Prominent examples of tertiray tasks include changing the audio source (e.g., radio station, playlist, etc.), reacting

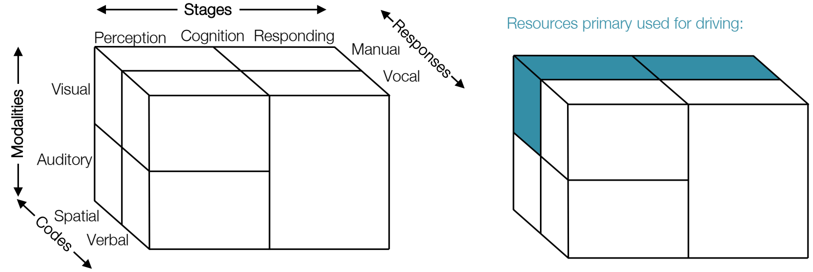

Figure 3.2: Wicken's Muliple Resource Theory and resource allocation of the primary driving task as a visual-spatial manual task (based on [251]).

to an incoming phone call, and controlling the climate settings. Typically, the driver conducts tertiary tasks simultaneously with primary and secondary tasks, consequently while driving. Figure 3.1 demonstrates that the input devices of the 2015 BMW 7 series can be assigned to the three classes of the driving task [233]. While primary and secondary devices are placed close to the driver, the use of tertiary controls commonly requires more physical effort.

Note, that the driving task is often split into two instead of three classes [255]. In this case, secondary tasks comprise the secondary and tertiary driving task of the trisected definition. In this thesis, we heavily use the term secondary task referring to both secondary and tertiary tasks.

3.1.2 Information Processing

As the driver is confronted with various concurrent tasks while driving, automotive UI designers have to understand how the driver processes this huge amount of information. In general, information processing consists of three stages [207]: Environmental information is identified (stimulus identification) and processed (response selection) in order to come up with a certain action (response programming). In this process, several psychological constructs such as perception, attention, memory, cognition, and decision making play a crucial role. Please refer to the work of Wickens [253] for further information on these topics.

Information processing requires cognitive resources while the human's capacity of resources is generally limited. Workload describes the demand imposed by one or several tasks on the limited set of resources. If this demand exceeds the available capacity of resources, task performance collapses. Grier [79] describes this as the “red line of workload”. Since the driver has to handle various tasks while driving, the management of the available cognitive resources is crucial. The *Multiple Resource Theory* of Wickens [252] is one approach of understanding the performance in multitask environments. He defined three dichotomous dimensions of information processing: the stages (i.e., perception, cognition, responding), the codes (i.e., spatial, linguistic/verbal), and the modalities (i.e., visual, auditory). Wickens expresses these dimension in a cube (cf., Figure 3.2). Actually, there is a further dimension, the response, which represents the codes on the response side of information processing. If two tasks simultaneously address resources from the same levels along the defined dimensions (i.e., the rectangles of the cube), the interference between the tasks increases. In consequence, workload increases and can decrease task performance since multiple tasks compete for common perceptual resources. For example, entering a destination in the navigation system while driving results in an interference as both tasks require visual-manual resources. In the case of interacting with an S3D IC the spatial encoding of the secondary task can interfere with the spatial characteristics of the primary driving task. However, incompatible mappings are more difficult to process and hence a visual-spatial map may convey geographical information in a better way than words [251]. Note, that to the three dimensions a fourth was added later, the visual channel distinguishing between focal and peripheral vision.

Driving a vehicle requires the driver to perceive and understand the driving situation and to anticipate upcoming events. *Situation awareness* has a crucial influence on decision making and performance in complex dynamic environments [58]. According to Smith and Hancock [219], situation awareness is the appropriate knowledge of an environment allowing for performing a certain task. Endsley [58] provides an accepted model of situation awareness. It consists of three levels which precede a final decision and a resulting action. First, environmental information is perceived and transformed into an internal representation (perception). Second, a combination of the available information allows the understanding of the current situation and the relationships among objects (comprehension). Third, future actions of objects in the environment can be predicted due to their status and dynamics and the comprehension of the situation (projection). External factors such as individual attributes (e.g., ability, experience) but also system factors can influence situation awareness. As a result, the design of the UI can contribute to the driver’s situation awareness and hence can support decision making as well as performance. According to Starter and Woods [203], situation awareness consists of four components:

Spatial awareness: Knowing the individual position and spatial relations between objects.

Figure 3.3: Audi's virtual cockpit provides a classic (left) and infotainment view (right) in its instrument cluster (pictures taken from website[11]).

Identity awareness: Knowing the individual tasks and goals.

Responsibility awareness: Knowledge about the individual control over tasks.

Temporal awareness: Knowing temporal sequences.

In particular, we envision to foster the driver's spatial awareness by using S3D for designing in-car UIs. In the following, we present prominent display locations in the car which can be potentially enhanced by the usage of 3D displays.

3.1.3 Design Space of Visual Displays

In accordance to Kern and Schmidt [122], the driver-based design space of automotive UIs addresses input and output devices in regard to their modality and placement. As we already demonstrated the location of available input devices in the car (remember Figure 3.1), we introduce the state of the art of prominent in-car display locations in the following.

Instrument Cluster (IC)

The IC, also called instrument panel or display, is located behind the steering wheel and has been a standard element in vehicles since 1910 [158]. During recent years, analogue displays for speed, rpm, odometer, fuel level, motor temperature, warning telltales, and indicators are increasingly substituted by digital display technologies [172], which allow the visualization of additional content. At the moment, several automobile manufacturers launch cars with fully digital ICs. Figure 3.3 shows the vitual cockpit[11] of Audi. The 12.3" TFT display allows the driver to choose between two different views. A classic view shows

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[11] http://www.audi.com/com/brand/en/vorsprung_durch_technik/content/2014/03/audi-virtual-cockpit.html, last accessed September 12, 2015.

dominant gauges for speed and rpm whereas the infotainment view provides a direct access to the navigation system, media lists, and communication functions. A multifunctional steering wheel allows for controlling the displayed content. The 2015 BMW 7 series as well as the 2013 Mercedes S-Class also provide the control of infotainment and driver assistance systems displayed in a digital IC using multifunctional buttons on the steering wheel. All mentioned examples use 3D graphics in order to give their ICs a spatial layout. Nevertheless, the applied displays use monoscopic depth cues and do not support the use of S3D.

Gryc outlined five reasons for the increasing adoption of digital ICs[12]. They are *reusable* as the same hardware components can be deployed across various vehicles while the software as well as the GUI allow for a differentiation. In accordance, updating the software enables the integration of novel functions contributing to the system's *scalability*. *Dynamic* information presentations enable the personalization and the staging of the current driving mode (e.g., sport, comfort, eco), which can increase the *attractiveness* of the vehicle due to compelling graphics and animations. Moreover, the displayed content can be adapted due to the physiological and psychological state of the driver as well as the current driving situation if future cars can accurately assess these contexts [138]. In this way, digital displays can solely present information currently required in order to increase the *usability* of the UI by avoiding information overload and visual tunneling. Particularly, in demanding driving situations reduced visual load can support the driver in the primary task.

During recent years, several automotive manufacturers and suppliers presented show cars equipped with MLDs or autostereoscopic display technologies showing 3D displays as future trend for automotive ICs (cf., Section 1.1). Also research draws attention on the in-car use of 3D displays, in particular for the IC [22, 128, 182, 230]. Please refer to Section 8.1 for detailed information about related work on S3D presentations in the car.

Center Information Display (CID)

In various modern cars a display in the center console, the central information display (CID), provides access to multiple tertiary functions, organized in hierarchical menu structures [233]. Typically a rotary remote control device (cf., Figure 3.1 which illustrates BMW's iDrive controller) or a touch sensitive screen allow the user to interact with these in-vehicle information systems (IVIS)[13]. Moreover,

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[12] http://electronicdesign.com/automotive/design-challenges-digital-instrument-clusters, last accessed September 12, 2015.

[13] IVIS inform and entertain the driver [233].

BMW introduced with its 7 series in 2015 mid-air gestures for simple tertiary tasks such as controlling the volume and accepting or rejecting a call. In the future, we expect an increasing use of further interaction modalities enhancing the natural interaction with automotive UIs such as haptic feedback [192], natural speech interaction [141,247], gaze [5,121], as well as multimodal approaches [181]. Future trends regarding the display technology of the CID point to large as well as shaped display formats [196] as the Model S of Tesla impressively demonstrates[14].

Head-Up Display (HUD)

Many automotive manufacturers launch HUDs in their cars, particularly in upper class vehicles [233]. Automotive HUDs present a transparent image behind the windshield close to the driver's line of sight in a viewing distance of ca. 2 m [157]. The driver perceives a virtual image in front of the car since the HUD utilizes the windshield as a partly reflecting mirror. Typically, the HUD shows the current speed, navigation cues, as well as warnings and information from advanced driving assistance systems such as ACC (cf., Figure 3.4). In addition, the 2015 BMW 7 series also offers frequently used infotainment functions in the HUD which the driver can manipulate using multifunctional controls on the steering wheel. In contrast to the IC and the CID, the driver is not forced to look down and to permanently perform costly focus switches between the display and the driving scene. The large projection distance of the HUD decreases these changes in focus and thereby increases safety and comfort [233, 254]. Milicic and Lindberg [157] show that a HUD can improve secondary task performance as well as driving performance, compared to a head-down display (i.e., a CID).

Currently, AR HUDs, also called contact-analog HUDs, are developed which are able to superimpose the driving environment with virtual elements [234] as Figure 3.4 illustrates. This requires to adjust monocular as well as binocular depth cues of the virtual content in accordance with the real world. As the effectiveness of accommodation and convergence but also of binocular disparity decreases for large viewing distances, Bergmeier [12] propose an AR HUD with a projection distance of 50 m. Bergmeier shows that monoscopic cues are sufficient for presenting spatial augmentations of the real world at far distances. Israel et al. [110] used a tilted image source for investigating variants for an AR HUD in a real-world study. The used display concept projects the virtual image horizontally on the street and tilts it to an almost upright image at its distant end. Israel et al. showed that the used AR HUD reduces the driver workload significantly but does not affect the driving performance.

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[14] http://www.teslamotors.com/models, last accessed September 12, 2015.

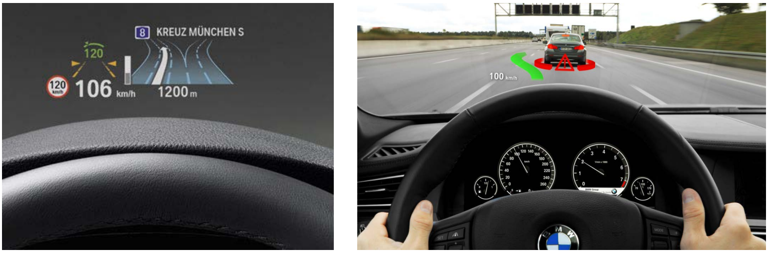

Figure 3.4: The HUD shows information in the driver's line of sight. While current HUDs show information on one depth plane (left image[a]) future AR HUDs superimpose the driving environment (right image[b]).

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[a] taken from https://www.press.bmwgroup.com last accessed September 12, 2015.

[b] taken from http://www.bmw.com last accessed September 12, 2015.

3.1.4 Design Guidelines, Principles, and Standards

Developing automotive UIs requires not alone to adhere to traditional usability principles from human-computer interaction (HCI) defined by Sneiderman [216] and Nielsen [167] (e.g., visibility of the system status, error prevention, feedback, consistency, aesthetics) but to fulfill car-specific requirements in order to minimize driver distraction (e.g., interruptibility, readability). Several organizations established principles, guidelines, and recommendations for the development of IVIS. The University of Michigan Transportation Research Institute (UMTRI) provides access to the major telematics guidelines[17]. Some examples are the European Statement of Principles (ESOP) of the European Commission [41], the principles of the Alliance of Automobile Manufacturers (AAM) [1], the Japan Automobile Manufacturers Association (JAMA) [112], and the US National Highway Traffic Safety Administration (NHTSA) [166]. In summary, these principles address the overall system design, the installation of visual displays, presentation and interaction principles as well as system behavior and documentation. For this thesis, recommendations pertaining visual information presentation and display installation are highly relevant. In accordance, the system should not distract or visually entertain the driver. However, the driver should be able to obtain relevant information with a view glances, brief enough not to negatively affect the driving behavior. Information with higher safety relevance should be visually prioritized. Regarding the installation of visual displays, glare and reflections should be

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[17] http://www.umich.edu/d̃riving/safety/guidelines.html, last accessed October 18, 2015.

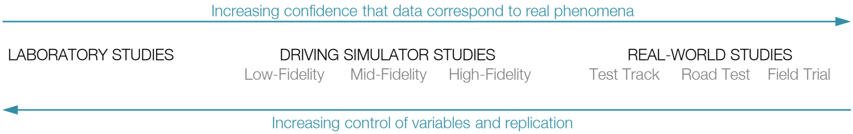

Figure 3.5: Test environments for in-car UIs and relationship between internal and ecological validity (redrawn from [33]).

avoided. The display should be positioned as close as practicable to the driver's normal line of sight but without obstructing primary vehicle controls and the road scene. As these guidelines are rather of a general nature, UMTRI [78] also provides some system specific guidelines, for example, for navigation systems as well as warning massages.

Some of the mentioned documents refer and also provide an overview on relevant standards of the International Organization for Standardization (ISO) [1,41]. Of prior interest for this thesis is the ISO:15008 document [106], which defines minimum requirements for dynamic visual presentations in vehicles such as display luminance, contrast, color combinations, and character size (e.g., the recommended minimum character size is 24 arc-min).

3.1.5 Evaluation

Beside standards addressing design and ergonomic aspects of IVIS, there are several accepted methods allowing the objective, reliable, and valid evaluation of in-car systems and their use while driving. Burnett [33] considers three factors for choosing a method for testing in-car systems: the test environment (i.e., laboratory, simulator, road), the task manipulation (i.e., multiple tasks, single task, no task at all), and the intended measures (i.e., subjective, objective). In the following, we give an overview on different test environments and introduce objective as well as subjective measures which we applied for the studies presented in this thesis.

Test Environment

Figure 3.5 summarizes the multiple test environments and their relation to internal as well as external and ecological validity. While laboratory setups allow an intense control over confounding factors real road environments maximize the confidence that the data correspond and are generalizable to real phenomena.

Real-World Studies: Driving studies in the real world comprise driving on a test track (i.e., a closed road), in real traffic with or without an examiner (i.e., road test), and in daily life (i.e., field test) by providing the participants a car equipped with tracking instruments (e.g., cameras) and the operational system under test. Field tests are used to evaluate effects of the long term use of a system, for example the acceptance of a new technology or adaptions in behavior [33]. One of the largest field studies represents the 100-Car Naturalistic Driving Study [50,164] which has logged the behavior of over 100 drivers for one year. The goal was to collect pre-crash data in order to identify causes for (near) crashes showing secondary tasks as major reason for driver distraction. However, field tests are quite expensive, require robust prototypes, and experimental conditions are uncontrolled [33, 126]. Although road and test track studies allow an increased experimental control compared to field tests there are still various confounding factors such as weather or traffic conditions. In addition to robust prototypes, a broad experimental design and procedure need to ensure safety for (traffic) participants and examiners. In general, due to the strong requirements on safety and robustness of the system, real-world studies are appropriate for late stages of the design process.

Simulator Studies: A powerful tool is the driving simulator as it provides a highly controlled and safe environment for investigating driver distraction [126, 190]. The fidelity of the simulator significantly impacts the effort in time and costs. High-fidelity simulators include full vehicle mock-ups, a close to 360° field of view, and a sophisticated motion system providing kinesthetic feedback. Mid-fidelity driving simulators feature a car mock-up with realistic controls in front of a large screen and sometimes a simple motion base. Low-fidelity simulators basically consist of a desktop workstation with simple controls such as a gaming steering wheel and pedals. Although driving simulators require less sophisticated prototypes and allow for testing various driving scenarios in a controlled and safe manner they entail also disadvantages. Learning effects in driving through the simulated environment, potential simulator sickness, and effects due to participants feeling observed are some examples. However, one major problem is the priority the driver gives to the primary and secondary driving task. Since errors in the primary driving task do not have serious consequences in the simulator the driving behavior there can significantly differ from driving in the real world [72].

Laboratory Studies: Laboratory studies do not require a driving task and allow a low cost evaluation in rather early stages of the development process. One example for a standardized laboratory method is the occlusion test [107]. The participants have to wear goggles which frequently occlude their visual field (simulating glances on the driving scene). Concurrently, the participants perform tasks on a computer monitor or in a stationary vehicle. Typical measures for occlusion tests are error rate, task completion time, and ease of resumption after interruption. Another approach suggests the AAM [1] for early development stages. A divided attention task requires the participants to perform two tasks simultaneously. A primary task loosely demands visual attention, for example for monitoring a video sequence showing a driving scene and pushing a button if a pedestrian appears [124], while the secondary task addresses the interaction with the system under test. Despite this allows for controlled, simple, and fast testing, these lab studies do not assess driving performance as well as the interference between driving and the investigated secondary task.

In summary, the reviewed test environments have certain advantages and disadvantages. In accordance, the choice of test environment highly depends on the development stage of the system but also on factors such as time, costs, and the experience of the development team.

Objective Measures

There are several methods that allow the assessment of objective data measuring the driver's performance and workload. The Lane Change Task (LCT) [108] is a standardized methodology evaluating the demand of a secondary task while driving in a simulated environment. The participants are requested to perform various lane change maneuvers while interacting with the system under test. The deviation between the driven trajectory and a defined optimum lane change maneuver (normative model) determines the primary driving quality and the impact of a secondary task. Another accepted method is the car-following test as proposed by the AAM [1] and the NHTSA [165, 166]. This test can be carried out in the driving simulator but also on test tracks and real roads. The driving task of the participants is to follow a lead vehicle which is driving at constant speed. The goal is to steadily keep the driving lane and to maintain a constant distance to the preceding vehicle. This allows lateral as well as longitudinal control to be measured while driving and performing a concurrent secondary task.

Primary Task Performance: For car-following tests typical measures for lateral control are the number of lane exceedences and the standard deviation of lateral position (SDLP) [1,77,165]. The SDLP describes the dispersion of lateral position $\{(x_0),...,(x_n)\}$ for n data points as follows:

$$SDLP = \sqrt{\frac{1}{n}\sum_{i=0}^{n}(|x_i - \bar{x}|)^2} \quad \text{with} \quad \bar{x} = \frac{1}{n}\sum_{i=0}^{n} x_i$$

Typically several secondary tasks occur for one condition. Then the SDLP describes the mean of the SDLP values calculated from the respective secondary task exposures. Beside lateral measures, longitudinal measures include the distance and time gap to the leading vehicle as well as the time to collision (TTC). Please refer to SAE standard J2944 [199] and Green [77] for a detailed overview of definitions for driving performance measures.

Secondary Task Performance: User performance in interacting with the system while driving can indicate the demand due to interferences between primary driving and secondary tasks [33, 88]. Measures such as task completion time (TCT), accuracy, and error rates reflect the effectiveness and efficiency of the system under test. Additionally, detection response tasks (DRTs) can be used to measure visual or mental workload [109]. Those tasks require the participants to react as fast as possible on a presented stimulus which can be of visual (peripheral detection task [111]), haptic or auditive nature.

Eye Gaze Behavior: Measuring the eye glance behavior of the driver is an expressive mean for quantifying the visual distraction from the primary driving task [1, 75, 88]. Typical measures include number of glances on areas of interest, mean glance duration, maximum glance duration, and total eyes-off-the-road time [76]. As video taping the driver's eyes and manually analyzing the sequences is very time-consuming, sophisticated eye tracking systems such as Ergoneers' Dikablis[18] can be used to collect and analyze the gaze data.

Beside the presented methods, physiological measures as skin conductance and heart rate, are sensitive in measuring workload while driving [151,208]. Moreover, computational cognitive models such as Distract-R [200] or MI-AUI [209] allow the developer to predict primary and secondary task performance for IVIS prototypes. Such approaches are suitable for a quick evaluation of early prototypes without conducting time-consuming user studies.

Subjective Measures

The users' opinion about a system is crucial for its success. Some aspects of interactive systems, such as acceptance or attractiveness, can be solely assessed through subjective methods. In addition, subjective data can validate and clarify objective results. Expert studies as well as heuristic evaluations, focus groups, interviews, and questionnaires are common methods in HCI and serve also for evaluating in-car UIs [33, 88]. An heuristic evaluation requires experts to judge

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[18] http://real.psych.ubc.ca/images/9/9b/SW_Dikablis_Handbuch_V2.0_ENG.pdf, last accessed September 4, 2015.

aspects of a system in regard to specific principles and heuristics. In the case of an automotive system, common principles and guidelines provided by UMTRI [78], AAM [1], JAMA [112] and the EU [41] (please refer to Section 3.1.4) can be used. In the following, we shortly introduce the questionnaires applied in the studies which this thesis presents.

Workload: While self-ratings on mental workload may appear questionable, Gopher et al. [74] show that self-assessment can provide reliable insights into cognitive load. A common questionnaire assessing the user's workload is the NASA Task Load Index (NASA TLX) [87]. The Driving Activity Load Index (DALI) [178] is the adapted version of the NASA TLX for automotive settings. The items of the DALI (e.g., effort of attention, visual demand, stress, interference between driving and system use) are rated on a six-point scale. A weighted procedure allows the calculation of a global score.

Usability, Attractiveness, and Acceptance: Perceived usability as well as hedonic qualities such as attractiveness and aesthetics have a major influence on the acceptance of new in-vehicle technologies [189]. The AttrakDiff [89] as well as the INTUI [237] are questionnaires that address pragmatic as well as hedonic qualities of an interactive product. The items of both questionnaires are semantic differentials rated on seven-point Likert scales. The INTUI groups its 16 items into four components (effortlessness, gut feeling, magical experience, verbalizability) while the AttrakDiff measures three dimensions, pragmatic quality (PQ), hedonic quality (HQ), and attractiveness (ATTR), using 21 items. For our studies, we use a short version of the AttrakDiff which covers all dimensions with ten items [90]. Measuring the perceived usability the System Usability Scale (SUS) contains 10 statements which are rated on a five-point Likert scale. The SUS allows the calculation of a global score between 0 and 100. Scores above 80 prove a high usability of the system.

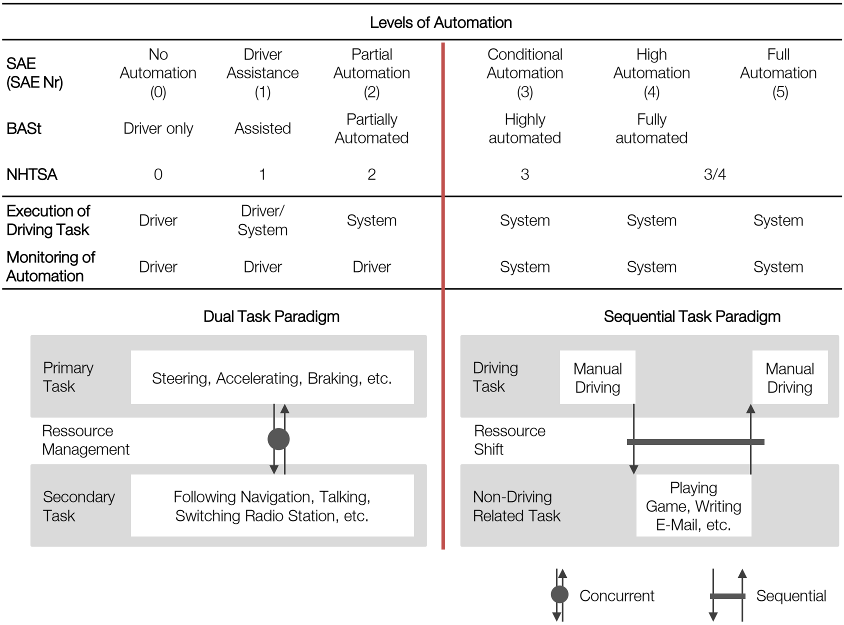
Visual Discomfort: As our research is about the use of 3D displays while driving, we use the SSQ [120] for measuring visual discomfort induced by the in-car system. In the automotive domain, this questionnaire is typically used to evaluate sickness symptoms due to driving in a simulator. Conversely, we apply the SSQ for evaluating S3D automotive UIs. The questionnaire measures nausea, oculomotor, and disorientation with 16 items rated on a four-point scale. It also provides a global sickness score. Please refer to Mehlitz [152] for a correct calculation of the scores.

3.2 From Manual to Automated Driving

Currently, many automotive manufactures as well as companies such as Google drive the development of highly automated and autonomous cars. Nowadays cars equipped with advanced driver assistance systems which take over lateral (i.e., lane keeping assistant) as well as longitudinal control (i.e., ACC) require the driver to monitor the automation as primary task and allow for performing simple secondary tasks at the same time. In contrast, highly automated driving enables the driver to avert the attention from the primary task and to fully engage in other activities. As highly automated driving is currently under tested with experimental vehicles on our roads today, it is just a question of time when the first highly automated cars are launched on the market. In this Section, we provide an overview on the different automation levels and describe the fundamental changes for the driver while highly automated driving in contrast to manual driving situations. The comparison of both driving paradigms allows us to suggest a new terminology according to the level of automation.

3.2.1 Levels of Automation

As automation technologies have been increasingly applied in different industry sectors, a wide variety of definitions for levels of automation has been used in the corresponding research communities. Meanwhile, international and national organizations gave clear and more specific definitions for the levels of automation, ranging from “driver only” (manual) to “fully automated” (BASt, Gasser et al. [67]), level 0 to level 4 (NHTSA [236]) or “no automation” to “full automation” (SAE [198]). Please refer to Figure 3.6 for an overview of the definitions. For level 0 the driver performs the driving task without active assistance from the vehicle. Level 1 allows the driver to disengage from aspects of the primary task (i.e., longitudinal or lateral control). If the vehicle controls both longitudinal and lateral position and the driver concurrently needs to monitor the automation in order to intervene as necessary, level 2 applies. In contrast, level 3 does not require the monitoring of the automation but expects the driver to respond appropriately in the case of a take-over request (TOR). Finally, level 4 and 5 (SAE definition) do not force the driver to appropriately take over the driving task with level 5 automation is able to handle all roadway and environmental conditions. In the remainder of this chapter, the stated levels are based on the SAE definition [198].



Levels of Automation						
SAE (SAE Nr)	No Automation (0)	Driver Assistance (1)	Partial Automation (2)	Conditional Automation (3)	High Automation (4)	Full Automation (5)
BASt	Driver only	Assisted	Partially Automated	Highly automated	Fully automated	
NHTSA	0	1	2	3	3/4	
Execution of Driving Task	Driver	Driver/ System	System	System	System	System
Monitoring of Automation	Driver	Driver	Driver	System	System	System

Figure 3.6: Today, in-car information systems allow the driver to manage simple and interruptable tasks beside the primary task. This is referred as dual task paradigm (cf., left side). With the advent of highly automated driving we expect a paradigm shift to switching the full attention between the driving and non-driving related task. We introduce this task management model as sequential task paradigm (cf., right side). Please note, that for high automation levels (level 4 & 5) the driving task can be even fully omitted (the summary of the automation levels is based on [218]).

3.2.2 A Paradigm Shift: From Dual Task to Sequential Task Management

In accordance with the levels of automated driving, we can classify prior work about automotive UIs. We claim that research on lower automation levels focus on a different task paradigm than higher automation levels. Figure 3.6 illustrates the underlying paradigm for the different automation levels. In the following, the two underlying paradigms are presented in more detail.

In computer science multitasking defines the execution of more than one process at the same period of time. Psychology matches this principle to humans by defining human multitasking as “the ability to conduct two or more tasks at the same time both requiring attention and various advanced cognitive processes” [242]. Since human processing theories commonly have their origins in models of computer science, computational frameworks were developed which simulate human cognition. Act-R allows to model a wide range of higher level cognitive processes, for example, human-computer interaction [6]. Based on Act-R Salvucci et al. [201] proposed that multitasking behavior can be represented along a single continuum in terms of the time spent on one task before switching to another. This continuum ranges from concurrent tasks with rapid switching (milliseconds to minutes) to sequential tasks with longer time between switching (minutes to hours). Based on the theory of Salvucci et al. we characterize and compare the task management for lower and higher automation levels[19].

Dual Task Paradigm

During manual (level 0), assisted (level 1), and partially automated (level 2) driving, the driving task can never be abandoned entirely. The driver needs to continually adjust the allocation of resources to both the primary task, longitudinal and/or lateral control (level 0 & 1) or monitoring the automation (level 2), and secondary tasks, for example dealing with the navigation system or tuning a radio [190]. As the previous Section demonstrates, a lot of research exists about dual task management for the automotive domain, ranging from modeling information processing [97,253] and driver distraction [200] over defining evaluation standards for automotive UIs [108] to design principles for IVIS [1]. In the multitask continuum of Salvucci et al. [201], the “execution of two or more tasks at the same time” is considered as concurrent multitasking. As a real-world example, the authors cite research on driver distraction “where a driver performs a secondary task (e.g., dialing a cell phone) while controlling a vehicle”.

Sequential Task Paradigm

During automated driving, however, “the vehicle is designed so that the driver is not expected to constantly monitor the roadway while driving” anymore, referring to automation levels higher or equal 3 [236]. In contrast to lower levels of automation, a longer time might be spent on one task before switching to another. For instance, the driver might read a book for several minutes until they decide

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[19] The presented terminology and its deduction is the result of intense discussions with my colleagues at BMW, namely Lutz Lorenz, Sebastian Hergeth, and Philipp Kerschbaum.

or is requested by the system to take over the driving task. Therefore, we argue that multitasking in the context of higher automation levels (≥ 3) should be considered as sequential multitasking, following Salvucci et al. [201]. In order to avoid conceptual confusion and discern research in the domain of automated driving from earlier research on lower levels of automation, we do not use the word “multitasking”. Instead, we refer to our proposed notation as the *sequential task paradigm*.

Definition. *The sequential task paradigm addresses automation levels higher or equal 3. If the vehicle state shifts between a lower automation level (< 3) and a higher automation level (≥ 3) a sequential task switch between the driving task and a non-driving related task occurs. Note, that some automation levels (≥ 4) include cars without primary input devices such as the Google self-driving car*[20]. *As these vehicles do not allow the engagement in driving at all, task switching between driving and non-driving related tasks practically drops.*

We also suggest that the common categorization of primary and secondary driving tasks is not applicable to automation levels higher or equal 3. During automated driving, the actions necessary for vehicle positioning (i.e., primary tasks) are performed by the car and do not require the driver to monitor the driving environment. As a result the driver is not involved in the control loop anymore. Hence, there is no more use in labeling tasks as secondary in the context of the sequential task paradigm.

Definition. *Non-driving related tasks are independent from driving and can be equal to secondary tasks which occur during low automation levels (e.g., switching the radio station). In contrast to secondary tasks, the driver can draw the full attention on the non-driving related task. This enables further activities such as gaming and writing complex text documents while the car takes care of driving.*

3.2.3 Highly Automated Driving

Highly automated driving (level 3) allows the driver to deal with non-driving related tasks. The automation system is able to provide the highly automated driving mode under certain conditions. If these conditions are not met anymore or any kind of malfunction is detected, a TOR is triggered. Hence, the transition from the non-driving related task to the driving task can be either driver initiated or

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[20] http://www.google.com/selfdrivingcar/, last accessed September 12, 2015.

system initiated due to a TOR. The major interest of research in highly automated driving is the particular situation of a TOR. According to Salvucci et al. [201], the *interruption lag* is defined as the time between a warning of an impending interruption and the actual start of an interrupting task. This is very close to the description of a highly automated car "that can determine when the system is no longer able to support automation [...], and then signals to the driver to reengage in the driving task, providing the driver with an appropriate amount of transition time to safely regain manual control" [236]. As a result, the evaluation of highly automated systems focuses on the transition from the non-driving related task to the driving task instead of driver distraction. Hence, evaluation methods as well as UI design principles for manual driving can not be applied for those scenarios. Nevertheless, former research [46, 69, 142] established commonly used measures and take over situations for evaluating the driver behavior for the transition from highly automated to manual driving. The results of those studies inform the design of the automation system in order to optimally support the driver in taking over the driving task. Already investigated parameters are, for example, the time until the system can not manage automation anymore [46, 69], the visualization of the recommended driver reaction [142], and the influence of brake applications during the take over process [70].

However, there is a lack of knowledge about the impact of the non-driving related task on the take-over capabilities of the driver. Beside the effect of the traffic situation, Radlmayr et al. [185] investigated the effect of two task types as non-driving related task on the take over performance. They used two standardized tasks with the Surrogate Reference Task (SuRT) [105] addressing visual and cognitive load and the n-back task [191] inducing solely cognitive load. They found that the SuRT and the n-back task show similar effects on the take over process. To our knowledge, this is the only study addressing variants of the non-driving related task. We argue that those investigations are in inherent need since they inform the design of applications which can be used during highly automated driving and support the driver in the sequential task management.

3.3 Summary and Research Directions

In this chapter, we introduced the complex domain of automotive UIs. Regarding conventional driving which requires the management of several different tasks simultaneously, there are established principles, guidelines, models, and methods supporting and specifying the development and evaluation of in-car systems. A review of current display locations in the car pointed towards interesting directions for enhancing the UI with a S3D effect. Particularly, the IC as well as the HUD are promising starting points for three reasons.

1. In general, in-car 3D displays should not force the driver to use glasses or any kind of head gear for generating a smooth S3D impression. The IC and the HUD are primary visible and accessible by the driver. In contrast, the CID is visible for all car occupants and often operated by the co-passenger. Consequently, the CID would require a complex multiview S3D system while single-view 3D displays are sufficient for the IC and HUD.
2. Modern ICs and HUDs convey information of several classes, ranging from urgent warnings and frequently required data about the vehicle state (e.g., speed) to navigation and entertainment functions. Trends towards the digitalization of the IC as well as AR HUDs further foster a growing density and complexity of information and functions. Structuring information via S3D depth can be a promising approach for presenting relevant information to the driver in a fast and easy-to-understand way.
3. Many elements in modern ICs and HUDs represent spatial and temporal relations of the current driving context such as navigation cues and advanced driver assistance systems (e.g., ACC). Particularly, this is the major purpose of future AR HUDs superimposing the real 3D driving environment. We assume that S3D can support the unambiguous visualization of elements which require spatial awareness and a mapping between the virtual and real 3D world.

The advent of autonomous driving radically changes the requirements for automotive UIs. In this chapter, we presented the different levels of automation and the fundamental underlying interaction paradigms. Currently, interest in research about the interaction with automated and autonomous cars strongly grows. In the case of highly automated driving the immediate task switch from a non-driving related task to the driving task unfolds challenges for the UI design. In particular, it is essential to understand how the UI impacts the driver on getting back into the loop. In summary, we claim that for new in-car UI technologies such as 3D displays both extremes, manual driving and autonomous driving, as well as the transition between both driving modes need to be considered. As a result, this thesis investigates effects of interacting with a 3D display during manual driving as well as highly automated driving in the particular situation of a sudden TOR.

III

DESIGN PRINCIPLES

OUTLINE

In order to achieve the maximum benefit of S3D for designing a UI, it is necessary to understand how depth positions should be chosen. There are two requirements which the depth layout of the interface has to fulfill. First, the depth budget used has to be comfortably perceivable for the user. Second, the user should be able to detect the depth structure instantly and correctly.

In this part, we take a closer look at these two requirements for applying S3D to automotive UIs.

- **Chapter 4 – Comfort Zone.** The comfort zone of a 3D display defines a depth range in which the user can comfortably perceive the displayed content. However, recommended as well as individual defined comfort zones reveal high variances. In this chapter, we present a method that allows for a decrease in the intersubject variance of the individual comfort zones. As part of this method, we define depth ranges that are comfortable to perceive for typical display locations in the car, in particular the IC and the HUD.
- **Chapter 5 – Depth Perception.** In this chapter, we investigate the human depth perception of stereoscopic content in highly controlled laboratory studies. With use cases for an IC in mind, we conducted three user studies providing insights into the use of 3D to structure elements in space. The findings allow us to identify depth ranges that maximize stereoscopic depth perception, minimal distances between depth layers which allow for an instant and correct discrimination of depth positions, and depth cues that maximize user experience. Pertaining the application of S3D for a HUD, we study the user's performance in judging depth locations of real world objects using virtual references.

Chapter 4

Comfort Zone

In the early 1950s, S3D display technology entered cinema and triggered a 3D hype with a release of more than 70 3D movies. However, the initial feeling of elation quickly declined for several reasons. One main cause for the decreasing interest was the feeling of discomfort during and after a visit in the movie theater due to the poor 3D quality. The quality of S3D visualizations depends on two major factors: the display technology and the 3D content design. While the display technology needs to optimize the separation of the left and right eye image, the content design has to consider the depth composition in order to avoid visual fatigue and discomfort. In particular, excessive parallaxes reduce the viewing comfort due to an increased decoupling of accommodation and convergence [215] and the loss of fusion [250]. As a result visual fatigue occurs, which can induce symptoms ranging from feeling pressure in the eyes to blurred vision, slowness of focus change, problems in perception, and even reduced concentration as well as work efficiency. This is less problematic for entertainment purposes compared to scenarios where users are potentially engaged in a further task, particularly if safety related such as driving. Obviously, S3D applications for in-car usage require a high visualization quality that does not confront the driver with additional visual and cognitive load. Moreover, we assume that the viewing quality has a direct impact on the findings when it comes to evaluating the S3D effect. A S3D system providing uncomfortable viewing conditions will not clarify its potential strengths compared to its 2D counterpart. For this reasons, it is necessary to assess the parallax limits that allow comfortable viewing conditions. These limits define the comfort zone.

Since the recommendations for parallax limits strongly vary between existing research we investigated the comfort zone in regard to its specific application in the automotive domain. This chapter presents two user studies that recommend parallax limits for integrating S3D displays into cars. In particular, we study appropriate comfort zones for the display locations of an instrument cluster (IC) and a head-up display (HUD). However, the highly controlled laboratory setting and the applied study desing allow the translation of the results to other application areas, for example, mobile devices and desktop environments.

This chapter is based on the following publications:

- N. Broy, F. Alt, S. Schneegass, N. Henze, and A. Schmidt. Perceiving Layered Information on 3D Displays Using Binocular Disparity. In *Proceedings of the 2013 International Symposium on Pervasive Displays*, PerDis '13, pages 61–66, New York, NY, USA, 2013. ACM
- N. Broy, S. Höckh, A. Frederiksen, M. Gilowski, J. Eichhorn, F. Naser, H. Jung, J. Niemann, M. Schell, A. Schmidt, and F. Alt. Exploring Design Parameters for a 3D Head-Up Display. In *Proceedings of the 2014 International Symposium on Pervasive Displays*, PerDis '14, pages 38–43, New York, NY, USA, 2014. ACM

4.1 Related Work

Although literature agrees on avoiding extreme parallaxes, recommended limits strongly vary [184]. Table 4.1 shows a summary of thresholds identified by former research using experimental or theoretical approaches. A common rule of thumb accepted and recommended in literature is the *one degree rule* which suggests not to exceed disparities of 60-70 arc-min [35, 129, 145, 148, 170]. However, there are studies that report lower limits [265]. In general, related work applies two different experimental approaches in determining the comfort zone. Either participants are exposed to a set of disparity conditions (e.g., [214, 262, 264]) or they are asked to adjust disparities to the limits of their personal comfort zone (e.g., [114, 260]). We argue that both approaches are necessary to determine a reasonable depth range. Hence, we first assess comfort zones via adjusting disparities and then examine the zone of comfort by investigating user performance for dedicated disparities in that range. Beside the different approaches, the experimental work

Table 4.1: Overview of parallax thresholds suggested by former research. This summary does not raise any claim to completeness.

Reference	**Parallax Threshold** (crossed; uncrossed)	**Approach**
Lambooij et al. (2009) [129]	(1°; 1°)	Theoretical: Defined by the characteristics of depth of focus and the human eye's aperture. Appendix I demonstrates the mathematical derivation.
Yano et al. (2004) [264]	(0.82°; 0.82°)	Experiment (N=6): Participants read a text at seven different parallax levels on a 23" shutter display at a viewing distance of 1.08 m.
Jones et al. (2001) [114]	(24 - 123 arc-min; 24 - 128 arc-min)	Experiment (N=8): Participants altered the depth in different scenes displayed on a 13.3" autostereoscopic display at a viewing distance of 0.7 m.
Wöpking (1995) [262]	(–; 35 arc-min)	Experiment (N=12): Participants rated viewing comfort for nine uncrossed disparity levels (0 - 140 arc-min) using a stereoscopic rear projection (screen size: 166 x 120 cm) with polarizing filters at a viewing distance of 2.75 m
Yeh and Silverstein (1990) [265]	(27 arc-min; 24 arc-min)	Experiment (N=8): Participants rated if they can fuse or not fuse a T shape at various disparity levels on a shutter display (diagonal: 40.6 cm) at a viewing distance of 66.04 cm.

is based on small sample sizes (n < 12), specific 3D output devices, as well as defined viewing distances.

In contrast, Shibata et al. [214] investigate the comfort zone for three viewing distances. They suggest a model for calculating the zone of comfort depending on the findings of two experiments. The results of the both studies reveal, first, that the decoupling of accommodation and convergence for a given dioptric value causes slightly more discomfort at far than at near distances and, second, that positive parallaxes are less comfortable at far distances while negative parallaxes are less comfortable at near distances. They provide the following formula to calculate the appropriate angular disparity to the front δ_{front} and back δ_{back} as a function of the viewing distance d_{screen}:

$$\delta_{\text{front}} = -2\arctan(\tfrac{i}{2d_{\text{screen}}}) + 2\arctan(\tfrac{i}{2m_{\text{near}}d_{\text{screen}}}(1 - T_{\text{near}}d_{\text{screen}})) \quad (4.1)$$

$$\delta_{\text{back}} = -2\arctan(\tfrac{i}{2d_{\text{screen}}}) + 2\arctan(\tfrac{i}{2m_{\text{far}}d_{\text{screen}}}(1 - T_{\text{far}}d_{\text{screen}})) \quad (4.2)$$

Using the recommended values for the constants (m_{far} = 1.035, $T_{\text{far}} = -0.626$, $m_{\text{near}} = 1.129$, and $T_{near} = 0.442$), a viewing distance of 75 cm, as it is the case for an automotive IC, and an interocular distance i of 6.3 cm (cf., [53]), the model suggests angular disparity limits of 1.96° to the front and 2.2° to the back. In regard to the limits of other research [114, 265], these values are very high. Moreover, the experiment of Jones et al. [114] shows that the comfort zone further decreases when the viewer is required to switch the visual focus between display and environment. This motivates this chapter to deliberately investigate the comfort zone of 3D displays for prominent locations in the car, namely the IC and the HUD.

4.2 3D Instrument Cluster

The IC is a look-down display providing information concerning the primary (e.g., speed), the secondary (e.g., indicator, navigation), and the tertiary (e.g., music player) driving task in a quite abstract way. When displaying this content stereoscopically, it is necessary to maintain a depth range from the screen which allows for a comfortable perception of the displayed content. We asked 21 participants to define their individual comfort zones by letting them alter the depth position of objects.

4.2.1 Prototype

We built a prototype that allows us to position objects in 3D space. The intention behind the design is to simulate a situation in which only binocular disparity and convergence are used as depth cues. In our initial work, we focus on the most simple use case of showing two distinct objects on the screen, drawing upon prior work by Froner et al. [66]. To minimize any influence of content, our prototype shows two squares of equal size positioned next to each other in the middle of the 3D display and at zero parallax. The distance between the inner edges of the two squares is 109 pixels. The width of the squares is 131 pixels each. Arbitrary textures can be added to the squares. For the purpose of the study, the z-position of each of the squares is altered in discrete steps – either explicitly using the keyboard, or automatically by using a script. We chose the smallest possible step size through specifying parallax sizes in pixels. For our setup (pixel pitch = 0.196 mm; viewing distance = 750 mm), -1 pixel parallax corresponds to 54 arc-sec of angular disparity, resulting in a perceived depth of 2.3 mm in front of the screen.

As we aim to isolate the effect of binocular disparity on viewing comfort for layered information presentation, the application eliminates other depth cues. We avoid any occlusion and ignore relative size by maintaining the initial size of the objects on the screen even as they are moved along the z-axis. This creates the impression of shrinking objects as they move towards the user and of growing objects as they move away. Through the exclusion of monocular cues, the 2D representation of the task shows no visible depth effect.

The prototype ran on an Asus G75VW notebook with a S3D screen. The system used the Nvidia 3D Vision 2 shutter technology to present scenes stereoscopically. Although automotive applications require autostereoscopic technologies, we deliberately opted for a shutter system since it provides high resolution 3D images with minimal stereoscopic artifacts such as crosstalk. We claim the high stereoscopic quality of shutter systems as a benchmark for in-car (auto)stereoscopic displays. The display used has a screen size of 17” with a resolution of 1920 x 1080 pixels. Since smaller screens are commonly used in the automotive domain we rendered the tasks on a centered area of the display with a resolution of 1280 x 480 pixels. The software was implemented using the game development engine Unity[21] with C# as scripting language.

4.2.2 Apparatus and Experimental Setup

The participants used the prototype described above to explore their personal comfort zone. Two keyboard buttons allowed for moving the squares forward and backward. By pressing the space bar the position was confirmed and the system recorded the disparity in pixels. Participants were seated in front of the system at a distance of 75 cm – the typical distance between driver and the IC. The look-down angle was less than 30° as recommended for in-car information displays [1]. A chin rest ensured a constant position of the participants.

4.2.3 Study Design

We used a repeated measures design to determine the maximal disparity still perceived as comfortable. The conditions varied due to three independent variables:

- **Content:** As we envisioned a potential effect based on the presented content, we tested *untextured* squares and squares *textured* with an arrow, as can be found in a navigation system.

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[21] https://unity3d.com/, last accessed October 19, 2015.

- **Direction:** Starting from the screen plane, we were interested in how far the comfort zone stretches to the *front* and to the *back* of the display.
- **Number of depth layers:** As information on 3D displays can be presented on several depth layers, we investigated the impact of their number. We distinguished between shifting both squares at once (*one depth layer*) and shifting just one of them (*two depth layers*) while the other remains at the initial position (zero parallax).

Each independent variable has two levels, resulting in eight conditions. We did not expect any sequence effects related to the assessment of the direction and the amount of depth layers. Therefore, we only counterbalanced the order of the content presentation. Half of the participants started with the plain squares (group A) and the other half with the squares containing an arrow (group B). As dependent variable we measured the absolute adjusted parallax value.

4.2.4 Procedure

Participants were recruited through our internal mailing list. As participants arrived, we provided them a brief introduction to S3D and explained them the course of the study. Participants first completed a demographic questionnaire (cf., Appendix III) and a stereo vision test based on RDSs [116] (cf., Appendix II). The stereo vision test consisted of 8 RDSs that depict different shapes. The parallax of the shapes was set to -1 pixel. The participants were then asked to identify the hidden shapes. If a participant recognized less than six of the eight presented RDSs correctly, they were excluded from the study. After participants successfully passed the test, the assessment of the comfort zone began.

First, the participants were asked to move *both squares* from the screen plane to the *front*. While exploring depth positions in front of the screen, the participants should deliberately leave their zone of comfort in order to experience uncomfortable depth settings. Then they had to find the maximum distance between the squares and the screen that is still comfortable to fuse. To ensure the adjusted depth setting the participants were instructed to avert their eyes from the screen for several seconds and focus on the squares again. If the refocusing was perceived as comfortable, they confirmed the depth position by pressing the space bar. Otherwise they readjusted the depth position and again ensured their settings by looking away from the display. After that, the same procedure took place for assessing the most comfortable depth position behind the display. Starting

Table 4.2: Descriptive statistics of parallax limits [pixel] for the IC.

Content	**Direction**	**Number of Depth layers**	
		One depth layer	Two depth layers
Untextured	front	$M = -168.9$, $SD = 106.3$	$M = -207.5$, $SD = 137.1$
	back	$M = 217.1$, $SD = 98.0$	$M = 193.3$, $SD = 102.1$
Textured	front	$M = -67.2$, $SD = 36.0$	$M = -66.0$, $SD = 32.8$
	back	$M = 72.9$, $SD = 35.2$	$M = 64.4$, $SD = 34.7$

again with *both squares* being shown on the screen plane, participants moved the squares to the *back*. There was no time limit for completing the task.

Next, participants moved *one square* from the screen plane to the *front* and *back* while the other square remained on the screen plane (zero parallax). As they did with both squares, the participants adjusted first the maximum positive and then the negative disparity that is still comfortable to fuse.

The participants repeated the described procedure twice: once using *untextured* and once using *textured* squares. After completing all tasks, they were asked about the difficulty for adjusting comfortable depth levels and about symptoms such as headache, eye strain, or motion sickness. In total, the study took roughly 20 minutes per participant.

4.2.5 Results

21 participants (7 female, 12 male) aged between 22 and 53 years ($M = 31.4, SD = 9.4$) took part in the study. We excluded 2 participants from the study. One recognized less than 6 out of the 8 presented RDS and one achieved extreme parallax values due to extreme shortsightedness. All participants have already experienced at least once stereoscopic content. Nevertheless, three participants had little experience viewing 3D images while nine have already viewed 3D several times, six several times per year, and one several times per month. 14 participants never felt discomfort because of the 3D effect, 3 sometimes and 2 always while looking at 3D images.

Table 4.2 shows the descriptive statistics of the comfort zone limits for all tested conditions. A repeated measures analysis of variance (ANOVA) reveals that adjusting only one square results in a significantly lower disparity compared to shifting both squares, $F(1,21) = 40.308, p < .001$. The other main effects as well as the interaction effects are not significant, all $p > .05$.

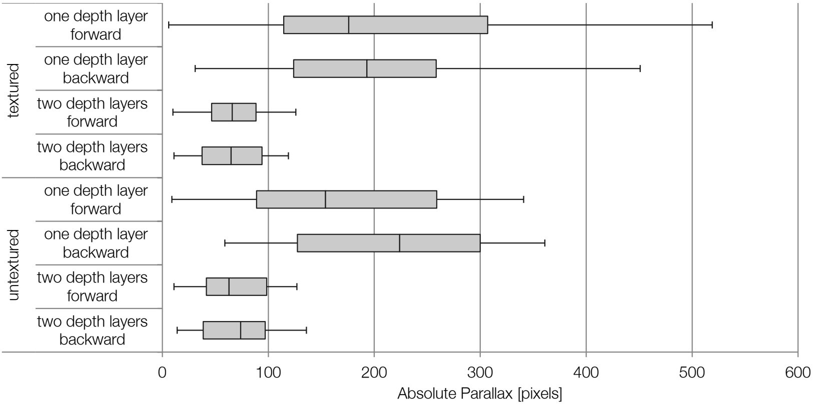

Figure 4.1: Box-Whisker-Diagramm of the parallaxes in pixels rated as comfortable. The pixel pitch of the used system is 0.196 mm.

Overall, the results reveal a very high variance between the participants as the box plot in Figure 4.1 shows. However, moving one square results in a lower variance and also in a smaller comfort zone. Although the subjects experienced depth values beyond their individual comfort zone, no symptoms associated to visual discomfort and fatigue were reported in the interviews. Nine participants spontaneously mentioned that the tasks with textured squares are easier than with non-textured squares. Using the data of textured squares at two depth layers we found a significant correlation ($r = -0.680, p = .001$) between the parallax thresholds and the rating of previous experienced discomfort due to stereoscopic content.

4.2.6 Discussion

The study revealed a significant difference between moving one square at a time and moving both squares together. We likely found no other significant effects because of high intra- and intersubject variance. Reasons for the high variances of the comfort zones among participants are of psychological or physiological nature, for example, individual interaxial distances [129], visual acuity [214], and prior experiences with stereoscopy [260]. However, adjusting one square at a time decreases the high variances. Since one square stays at the screen plane while the other defines the comfort zone, we assume that a reference object at the screen depth facilitates the assessment of participants' comfortable depth range. Moreover, a reference object at the screen plane also reduces the comfort zone. In consequence, presenting solely one depth layer allows the use of higher parallaxes than two depth layers. Still, it is questionable if additional depth layers further decrease the comfort zone.

Due to the high individual variances, systems that use binocular disparity for information presentation must either enable the users to define their individual comfort zone or use conservative limits. We assume that users generally appreciate a comfortable 3D effect that does not require them to previously decide and adjust their personal parallax limits. Consequently, we suggest the use of conservative parallax limits based on our data. As the results show similar parallax limits in the front and the back of the screen, we assume that the comfort zone is symmetrical and positive parallaxes may be applied in the same manner as negative parallaxes. Based on our data, we define the 75th percentile as recommendation for the comfort zone of a 3D IC. Using the data of textured squares on two depth layers results in parallaxes ranging from -40 to 40 pixels (35.9 arc-min angular disparity). This means 75% of the participants perceived this zone as comfortable for two textured objects on different depth layers. While the IC has similar characteristics as the CID (e.g., head-down, viewing distance, screen size, opaque display) the data of this study can also serve as a basis for a 3D CID. As the HUD significantly differs in its parameters from the CID and the IC, the following section addresses the comfort zone of a 3D HUD.

4.3 3D Head-Up Display

Typically, the HUD presents a transparent image at a projection distance of approximately 2 m in front of the driver. The current development of AR HUDs apply projection distances up to 15 m. As the HUD shows a transparent image in front of the dynamic road scenery, it does not support the presentation of low contrast content and detailed graphics. As a result, the presentation of monocular depth cues is limited in the HUD and stereoscopy can clarify spatial relations in an unambiguous way. However, this requires the identification of a depth range that allows the comfortable display of stereoscopic content. We aim to investigate the comfort zones of five different projection distances between 2 and 15 m. In accordance with the approach for a 3D IC (cf., Section 4.2), we asked 24 participants to alter the depth position of virtual objects to their individual comfort zone limits.

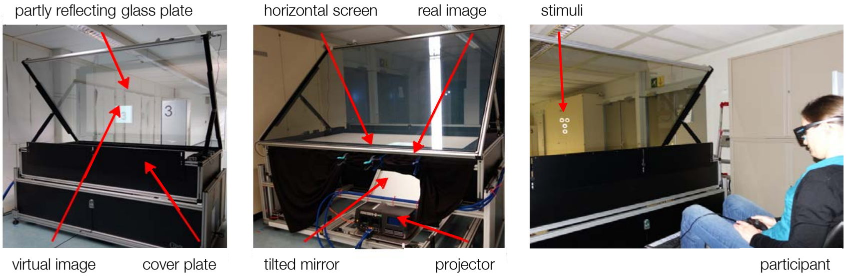

Figure 4.2: The images show the 3D HUD prototype from the front side (left image) and back side (middle image). In the right image, a participant adjusts the topmost ring to the limit of her personal comfort zone.

4.3.1 Prototype

A 3D emulator (cf., Figure 4.2) was built in the research laboratory of Bosch. It allows the generation of virtual stereoscopic images with variable projection distances and screen disparities. The projection distance defines the virtual screen distance (VSD) while the screen disparity specifies the depth position in front or behind the VSD. The resulting distance between driver and virtual image is the virtual image distance (VID). The projection unit is a Projectiondesign F35 AS3D projector, capable of presenting 3D images. It projects on a horizontal screen with a height of 95 cm via a tilted mirror inclined by 45 °. A glass plate with a visual reflectance of 40% and a size of 2,2 m x 1,6 m was mounted diagonally above the screen. Thus, the real image on the screen can be observed as a virtual image, superimposed with the surroundings. The system uses shutter technology and works with a frequency of 60 Hz per eye, resulting in a total frequency of 120 Hz. We applied an adapted version of the software Workbench3D[22] in which we could set parameters such as eye distance, VSD, and pixel size. Subsequently, the displayed virtual objects could be varied in parallax, position, and size. The user adapted the parallax of virtual objects by means of a game controller (Speedlink XEOX Pro Analog Gamepad). Binocular disparity was the only varying depth cue. Thus, the size of a virtual object was constant while its depth position changed. The look down angle of 0 ° was kept constant. To realize different VSDs, the emulator was mounted flexibly. A corridor of 22.4 m length allowed us to investigate a huge range of VSDs. To provide comparable surrounding

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[22] http://www.workbench3d.de/, last accessed October 6, 2015.

conditions, we adapted the illumination of the room and the homogeneity of the wall color.

As virtual content elements we used vertically aligned rings (cf., Figure 4.3 and 4.2), with an angular size of approximately 0.6°. The participants used the up and down buttons of a game pad to vary the depth position of the virtual rings. The system did not allow for adjusting positive parallaxes beyond the entered interpupillary distance. Thus, the prototype avoided diverging eye positions.

4.3.2 Study Design

The study followed a repeated measures design, exposing all participants to all combinations of the following independent variables.

- **VSD:** As we were interested in the effect of the VSD on the comfort zone, we investigated five different VSDs (2 m, 3 m, 5 m, 8 m, and 15 m).
- **Direction:** Starting from the respective VSD, the participants determined their individual comfort zone limit to the *front* (negative parallax) and to the *back* (positive parallax).
- **Number of depth layers:** In accordance with the previous study, we explored the impact of the amount of virtual depth layers on the comfort zone. We distinguish three cases: (1) the depth position of the three virtual rings is changed simultaneously (just *one* virtual depth layer is presented). (2) the depth position of just one ring is adjusted while the other two rings stay on the same layer, (*two* depth layers). (3) one ring is altered while the other two rings occupy different depth layers (*three* depth layers).

Since the adjustment of different VSDs required the rearrangement of the emulator, the study is divided into five parts – one for each VSD level. To avoid sequence effects we presented the different VSDs in a random order. We counterbalanced the combinations of the *direction* and the *number of depth layers* using a latin square. This results in $2 * 3 = 6$ combinations. Thus, we divided our test sample into six different groups that experienced the respective sequence of the *direction* and the *number of depth layers* combinations. Figure 4.3 shows the sequence for one of the six groups. For each group the respective sequence was obtained for each VSD part. As dependent variable we measured the absolute adjusted parallax value.

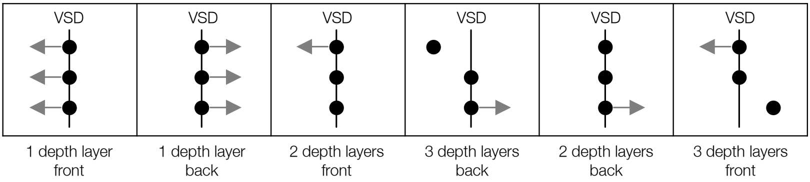

Figure 4.3: Sequence of the *direction* and the *number of depth layers* combinations for one of the six groups.

4.3.3 Procedure

We started each test session by asking about demographic data and former experiences with S3D. We measured the interpupillary distance of each participant with a pupillometer (Digitalpupillometer PD-6, VOG Hombach + Team GmbH) to calculate the respective VIDs depending on the VSD, the interocular distance, and the adjusted parallax value. Then we assessed general (corrected) visual acuity, using a Snellen test. Participants used both eyes simultaneously. We again used RDSs to test the ability of perceiving S3D content (cf., Appendix II).

If the participants successfully passed these tests, they explored the setup to get used to the system and the task. During this phase, we asked them to intentionally move the virtual object out of their comfort zone, so that the corresponding feeling could be experienced and recognized during the actual test. After that, the five VSD test condition blocks were presented following the study design. For each test condition the participants adjusted their individual comfort zone limits. During the adjustment, participants were asked to change their focus momentarily to a different point in the room, in accordance to the previous study's procedure. When the participants had decided on the limit of their personal comfort zone, they informed the experimenter who logged the value. In addition to the main task, we conducted a semi-structured interview to find out about the participant's subjective experience. We asked questions about the effort and discomfort the participant felt and about the subjective degree of task difficulty.

4.3.4 Results

In total, the results of 24 participants (5 female, 19 male) aged 27 to 74 years ($M = 46$, $SD = 11$) were evaluated. All 24 participants had normal or corrected to normal vision and passed the RDS test. Regarding the 3D experience, two

Table 4.3: Descriptive statistics of parallax limits [mm] for a 3D HUD.

VSD	Direction	Number of Depth Layers		
		One	Two	Three
2 m	front	$M = -103.9$, $SD = 72.4$	$M = -44.24$, $SD = 43.9$	$M = -38.5$, $SD = 43.5$
	back	$M = 53.5$, $SD = 13.0$	$M = 35.6$, $SD = 22.3$	$M = 28.7$, $SD = 23.6$
3 m	front	$M = -133.9$, $SD = 105.3$	$M = -65.5$, $SD = 43.4$	$M = -58.6$, $SD = 59.8$
	back	$M = 54.7$, $SD = 11.5$	$M = 60.2$, $SD = 20.3$	$M = 39.3$, $SD = 21.3$
5 m	front	$M = -194.0$, $SD = 178.4$	$M = -113.0$, $SD = 159.8$	$M = -107.5$, $SD = 129.0$
	back	$M = 56.5$, $SD = 13.5$	$M = 47.6$, $SD = 17.1$	$M = 43.1$, $SD = 19.4$
8 m	front	$M = -283.0$, $SD = 222.1$	$M = -152.0$, $SD = 185.4$	$M = 143.3$, $SD = 179.4$
	back	$M = 56.2$, $SD = 13.0$	$M = 49.7$, $SD = 15.5$	$M = 48.5$, $SD = 18.7$
15 m	front	$M = -488.6$, $SD = 366.5$	$M = -246.4$, $SD = 254.1$	$M = 253.4$, $SD = 305.6$
	back	$M = 51.4$, $SD = 18.3$	$M = 50.1$, $SD = 17.9$	$M = 50.0$, $SD = 19.8$

participants had never viewed 3D content before, four very rarely, twelve rarely, four occasionally, one often, and one very often. Ten participants have never suffered discomfort when it comes to viewing 3D content, ten sometimes, and four participants did not answer this question due to their little experience in watching 3D content.

Table 4.3 and Figure 4.4 present the descriptive statistics for the rated limits of parallaxes that provide comfortable viewing. Since a Kolmogorov-Smirnov test shows that our data is not normally distributed ($p < .05$), we used non parametric tests for the statistical analysis. We used Friedman tests for the main effects and Wilcoxon tests with Bonferroni corrected significance levels for pairwise comparisons. Comparing the different VSD levels with a Friedman test shows significant differences, $X^2(4) = 77.10$, $p < .001$. Wilcoxon tests show significant differences for all pairwise comparisons, $p < .005$, except for 3 vs. 5 m, $p = .006$. The number of depth layers has a significant influence on the parallax limits, as a Friedman test confirms, $X^2(2) = 37.33$, $p < .001$. Wilcoxon tests show that the participants can handle higher parallaxes for one than for two layers, $Z = -4.286$, $p < .001$, $r = -.619$, or three layers, $Z = -4.286$, $p < .001$, $r = -.619$. However, there are no significant differences between presenting two vs. three layers, $Z = -1.571$, $p = .116$, $r = -.227$. Finally, the absolute parallax limits for negative parallaxes are significantly higher than for positive parallaxes, $Z = -4.200$, $p < .001$, $r = -.606$.

The interviews revealed that most participants perceived the 3D effect as comfortable in general (92 %) and appreciated the effect for an automotive HUD (92 %).

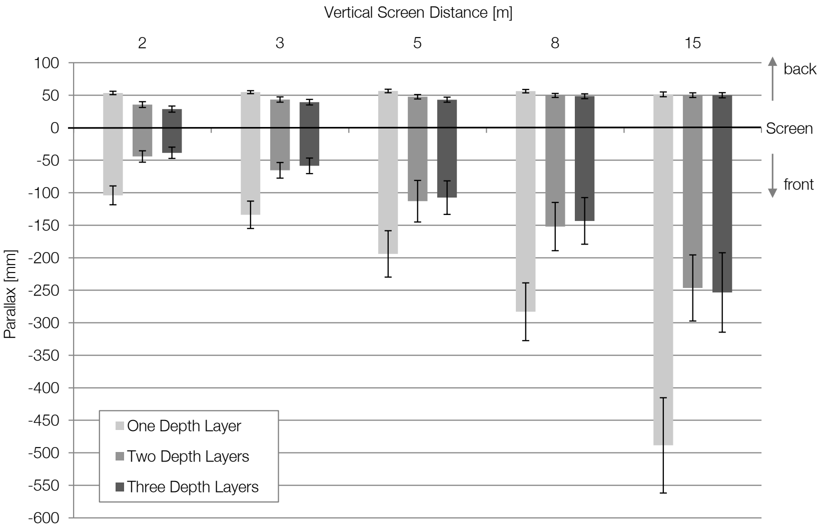

Figure 4.4: Means and standard errors of the individual parallax limits for a comfort zone.

33 % of the participants positively mentioned a VSD of 5 m, while there are just 29 % for 8 m, 25 % for 15 m, and 4 % for 3 m and none for 2 m. 29 % criticized the 2 m VSD. Only 8 % negatively commented on the 15 m VSD, 4 % on the 3 m VSD. The VSDs of 5 and 8 m did not receive any negative comments.

4.3.5 Discussion

Our results show that higher VSDs allow larger parallaxes to be presented. In accordance, Shibata et al. [214] show that there is a higher overall fatigue for near viewing distances compared to far viewing distances. They did not use a see-through display but viewing distances of 10 m, 77 cm, 40 cm, and 25 cm. In comparison, our study addresses several VIDs above 1 m and we aim to find values that define the comfort zone of the tested VSDs for a see-through display. Moreover, our previous study lets us assume that the comfort zone is symmetrical. In contrast, this study reveals that parallax thresholds are higher for negative than for positive parallaxes. This is in line with Shibata et al. [214] showing that positive parallaxes are less comfortable for far viewing distances. Note, that we prevented diverging eye positions by restricting positive parallaxes to the viewer's interpupillary distance.

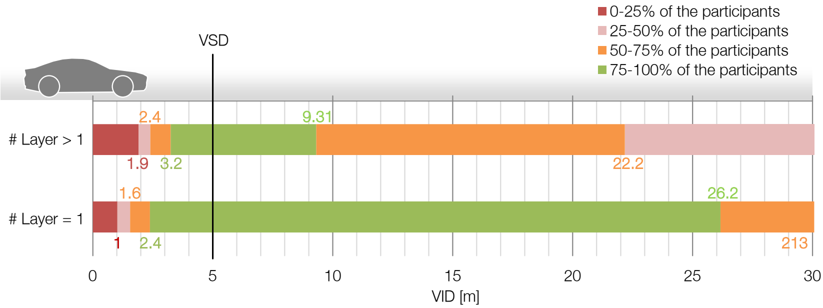

Figure 4.5: Comfort zone limits represented as distances from the VSD, which is 5 m in this case.

This study shows that the comfort zone significantly increases if solely one depth layer is presented in comparison to the use of several depth layers. This is in line with the findings of our previous study investigating the comfort zone for a 3D IC (cf., Section 4.2). However, the IC study did not investigate more than two layers. To complement the prior findings, this study additionally investigated the use of three depth layers. The results yield no significant differences between two and three depth layers. Thus, if two depth layers are occupied, the use of additional depth layers does not necessarily decrease the comfort zone. Furthermore, this finding has a methodical implication. It indicates that it is possible to assess the comfort zone by just distinguishing between one and multiple depth layers. The design of the multiple depth layer condition depends on the intended application.

In accordance with the previous study (cf., Section 4.2), we use the quartiles of the data to suggest conservative comfort zone limits. For each VSD * direction condition we found comfort zone limits by aggregating the data for the two and three depth layers condition. We aggregated the data due to the lack of statistical significances between the use of two and three depth layers. For the case of developing a stereo HUD, we identified a VSD between 5 m and 8 m as promising since it allows content from approximately 3 m up to 20 m in front of the driver to be shown. Figure 4.5 illustrates the difference between one and more depth layers for the comfort zone pertaining to a VSD of 5 m. The interested reader can find the comfort zone limits for the other investigated VSDs in the Appendix IV. We calculated the VIDs in respect to the measured interocular distance. The pupillometer used has an accuracy of measurement of 0.5 mm and hence a potential impact on the calculated VIDs. However, we assume that possible measurement errors are normally distributed and have no significant influence on our results.

4.4 Implications and Summary

This chapter presents the findings of two user studies assessing the depth ranges that allow for displaying comfortable S3D images. We deliberately opted for the display locations of an automotive IC and HUD. We assume that the comfort zone of a CID can be derived from our results of the 3D IC. Since our tests were conducted in highly controlled laboratory conditions and used artifical tasks as well as abstract content, we argue that the findings can serve as a basis for other application domains than automotive as well. The data of our studies let us derive comfort zones for viewing distances that range from 0.75 m to 15 m. Beside those thresholds, the outcomes allow us to define the following design principles:

- **Consider conservative parallax limits.** The comfortable viewing range of a 3D display strongly varies among individuals. As a result, systems that exploit 3D capabilities to present information should allow the user to determine a personal comfort zone or apply conservative parallax values. To reduce annoying interaction steps, we suggest the use of conservative limits which instantly provide a comfortable experience for most users.
- **Provide visual references at screen level.** As the interindividual variance decreases if one object remains as reference at screen depth, such depth layouts seem to facilitate the perception of the available 3D space. This suggests to use the screen layer as an anchor point for persistent information. More and less important information could then be aligned accordingly.
- **Choose virtual object positions carefully.** The use of one depth layer compared to the use of multiple depth layers has a significant effect on the comfort zone. While displaying one layer allows for comfortably covering a large depth range, multiple layers heavily narrow this range. This means that situations requiring large screen parallaxes can hide other depth layers to comfortably highlight the respective depth position.

In accordance with Shibata et al. [214], our studies show for far viewing distances higher thresholds for negative disparities than positive disparities. Moreover, Shibata et al. found that negative parallaxes are less comfortable for small viewing distances. In contrast, our study investigating the viewing distance of an IC shows no significant difference between positive or negative parallaxes. Nevertheless, interacting with objects located in front of the display can significantly differ from interacting with objects behind the screen layer. The next chapter addresses this question by investigating the user performance and depth perception in S3D space.

Chapter 5

Depth Perception

While viewing comfort plays a crucial role for the success of stereoscopic visualizations, the correct and quick perception of the depth layout is equally important. We envision to use stereoscopy for structuring information in order to enhance the user's perception and information processing. Thinking of automotive use cases, we consider the information architecture of two display locations, the instrument cluster (IC) and the head-up display (HUD).

For an IC, user interface elements that communicate a spatial and temporal analogy to the real world, such as navigation cues, can be presented in an easy-to-understand manner, for example, for judging the distance to the next turn action. Moreover, information can be structured on several depth layers. Less important content, for example inactive menus, could be displayed further in the back, while highly important information can even pop out of the screen, for example, a warning about the malfunction of a sensor. In this chapter, we report on three laboratory studies in order to understand depth perception for a 3D IC, which structures its information on separate depth layers. The first two studies investigate the user performance in depth perception for abstract depth layouts. In this way, we identify a minimum distance between two depth layers as well as a maximum amount of information layers. The third study explores the use of different depth cues. We present concrete IC concepts and evaluate the impact of monoscopic depth cues, stereoscopy, as well as motion parallax on user experience and usability.

Regarding the HUD, stereoscopic cues can be used to augment the real world at the appropriate depth location instead of a simple 2D overlay. For example, inconspicuous traffic participants such as pedestrians can be highlighted at their 3D location. We conducted a laboratory study with a 3D see-through display in order to understand the users' ability of judging real world depth positions with virtual 3D objects.

Overall, the presented user studies in this chapter contribute to the comprehension of human depth perception. As we mainly used abstract tasks as well as very controlled laboratory settings, most of our findings can be transferred to other application domains than automotive. This chapter concludes with a summary of general design principles which support designers to choose proper 3D parameters for maximizing the user's depth perception and user experience of their 3D application.

This chapter is based on the following publications:

- N. Broy, F. Alt, S. Schneegass, N. Henze, and A. Schmidt. Perceiving Layered Information on 3D Displays Using Binocular Disparity. In *Proceedings of the 2013 International Symposium on Pervasive Displays*, PerDis '13, pages 61–66, New York, NY, USA, 2013. ACM
- N. Broy, S. Schneegass, F. Alt, and A. Schmidt. FrameBox and MirrorBox: Tools and Guidelines to Support Designers in Prototyping Interfaces for 3D Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, pages 2037–2046, New York, NY, USA, 2014. ACM
- N. Broy, B. J. Zierer, S. Schneegass, and F. Alt. Exploring Virtual Depth for Automotive Instrument Cluster Concepts. In *Proceedings of the Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, CHI EA '14, pages 1783–1788, New York, NY, USA, 2014. ACM
- N. Broy, S. Höckh, A. Frederiksen, M. Gilowski, J. Eichhorn, F. Naser, H. Jung, J. Niemann, M. Schell, A. Schmidt, and F. Alt. Exploring Design Parameters for a 3D Head-Up Display. In *Proceedings of the 2014 International Symposium on Pervasive Displays*, PerDis '14, pages 38–43, New York, NY, USA, 2014. ACM

5.1 Discriminating Depth Layers

In the last chapter, we identified the boundaries of the comfort zone for the typical display setup of an in-car IC. In this chapter, we are interested to identify an area inside the comfort zone which maximizes performance for the user's depth perception. The task of the presented study requires the comprehension of a simple depth layout showing two objects on two separate depth layers. The goal is to quickly recognize the foremost object. The chosen task is based on the approach of Froner et al. [66]. While Froner et al. used this task to compare perception of fine depth differences for different 3D display technologies, we aim at comparing the perception of different depth layouts for the two objects. Particularly, we investigate how (a) the distance between the two objects at (b) different positions within the comfort zone impact on TCT and error rates. We tested four distances (i.e., screen parallaxes of 1, 2, 3, and 4 pixels) at five positions (i.e., screen parallaxes of -40, -20, 0, 20, 40 pixels, 0 pixels being the screen level).

5.1.1 Apparatus and Study Design

We used the same prototype which we applied for the assessment of the comfort zone (cf., Section 4.2) to display two squares on the screen. This time, the distance of the displayed items was not controlled by the user. Instead, we used a script to present the stimulus on the screen. The task was to decide quickly and accurately, which square was positioned closer to the user. The study was designed as a repeated measures experiment with the following independent variables:

- **Depth Location:** Observing the parallax limits of the comfort zone (cf., Section 4.2), we tested five depth locations of the displayed content. The depth locations were linearly distributed over the comfort zone at -40, -20, 0, 20, and 40 pixels parallax.
- **Depth Difference:** To determine the optimum depth distance between two items, we presented two squares with varying depth differences at each depth location. The difference between the squares' parallaxes were 1, 2, 3, or 4 pixels.

In order to counterbalance the horizontal position (left or right) of the foremost square as well as the depth distance of the squares to the reference layer (defined by the depth locations), we repeated each condition four times. For example, a depth difference of one pixel allows the presentation of one square at the respective depth location (e.g., 20 pixels) while the other square is located one pixel behind or in front of the reference layer. To minimize any effect that could occur due to the horizontal alignment of the squares, we placed once the left and once the right to the foremost position. In total, we investigated 20 conditions resulting in 80 stimuli that were presented to each participant in a randomized order. As content we used squares depicting an arrow (cf., Figure 5.1). We measured the TCT (i.e., the time between presenting the stimuli and the user making the decision which square points to the front) and error rates (i.e., percentage of incorrect responses). Between two tasks the participants had to solve a distractor task that requires them to focus cognitively and visually on a distractor display placed behind the 3D display. The distractor display showed words composed of two simple, unrelated nouns (e.g., kiwi-earring, fir-water). Participants were asked to read out the word shown on the display aloud. We applied the additional distractor task to satisfy requirements for real world applications that involve accommodation switches commonly occurring in pervasive display environments (e.g., automotive or mobile applications).

5.1.2 Experimental Setup and Procedure

Participants were provided a brief introduction to stereoscopy and a brief overview of the study as they arrived at the lab. In order to qualify for the study they had to pass a stereo vision test, based on RDSs [116] (cf., Appendix II), as well as a Snellen test [220], which measures visual acuity. Participants who passed the tests then proceeded with the main task. They were seated 75 cm in front of a 3D display. A chin rest was used to maintain the distance between the test person and the screen. A keyboard with two keys was provided – one representing the left square and one representing the right square. Participants were then asked to press the button for the square that appeared closer to them. There was no time limit but participants were asked to react as quickly and as accurately as possible. Then the 80 stimuli were presented in random order. After each stimulus we showed visual noise on the 3D display while the participants solved a distractor task on a TV screen placed 2 m in front of them. After that, pressing either of the two keys triggered the next stimulus to be shown after 500 ms in order to guarantee that users were already focused on the 3D display when the stimulus appeared and timing started.

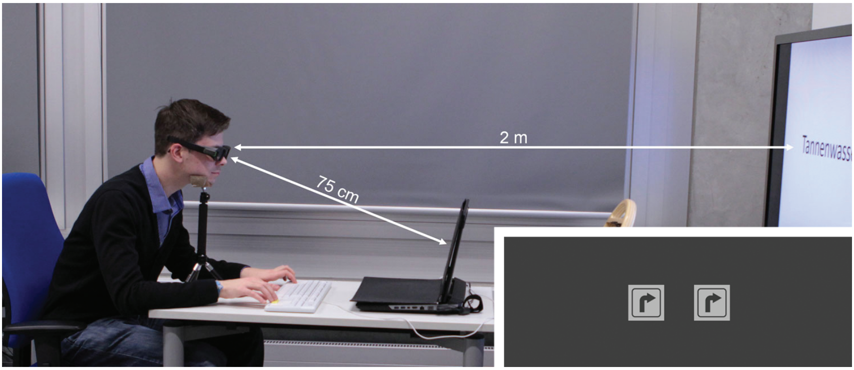

Figure 5.1: Study Setup: Participants were positioned at 75 cm in front of the stereoscopic display and at 2 m in front of the TV screen showing the distractor task. In the lower right corner the stimulus is shown.

To minimize learning effects, a set of 16 randomly chosen stimuli was presented in the beginning to each subject before seamlessly starting to show the 80 stimuli we prepared. Short breaks were taken after every 16th stimulus. At the end, we conducted semi-structured interviews with the participants. We were particularly interested in the difficulty of the task and the personal experience with the 3D effect with regard to visual fatigue and discomfort.

5.1.3 Results

In total, 18 participants (4 female, 14 male) aged 20 to 31 years ($M = 25.4$, $SD = 2.9$) completed the study. None of them participated in the experiments assessing the comfort zone. All subjects had corrected to normal visual acuity and had no problems in recognizing the -1 pixel RDSs.

Figure 5.2 presents the descriptive statistics for the TCT as well as error rate. Since Kolmogorov-Smirnov tests do not prove that the data are normally distributed, $p < .05$, we used non parametric tests for the statistical analysis. In general, the error rate is very low. We could not find any statistically significant effects in the correctness of the answers for the investigated *depth differences*, $X^2(3) = 7.538$, $p = .057$, as well as *depth locations*, $X^2(4) = 0.232$, $p = .994$.

Looking at the TCT for the different *depth differences* the plot of Figure 5.2 shows that the TCT decrease with increasing distance between front and back

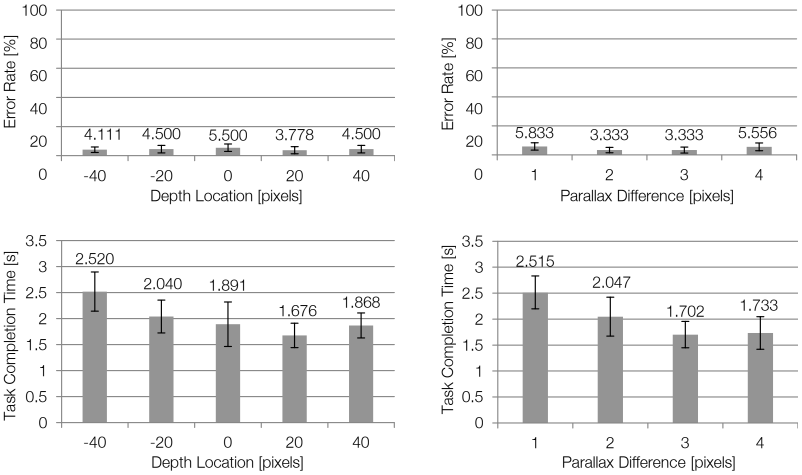

Figure 5.2: Means and standard errors for error rate and TCT.

square. This effect is statistically significant, $X^2(3) = 34.2$, $p < .001$. We performed a post-hoc analysis by means of Wilcoxon Signed Rank tests using a Bonferroni correction, resulting in a significance level set at $\alpha = 0.008$. All pair-wise comparisons reveal significant effects, $p < .005$, except the comparison of 3 and 4 pixel disparity, $Z = -0.719, p = .472$.

Analyzing the TCT for the different *depth locations* the plot in Figure 5.2 depicts higher TCTs for negative than positive parallaxes whereby TCT is lowest at 20 pixels. A Friedman test reveals a statistically significant effect, $X^2(4) = 36.978$, $p < .001$. Wilcoxon tests with a Holm-Bonferroni correction (cf., Table 5.1) show that for the foremost position of -40 pixels parallax reaction times are significantly higher compared to all other conditions, $p < .007$. At 20 pixels disparity, the TCT is significantly lower compared to the -20 parallax condition, $p = .002$.

The interviews revealed that none of the participants felt uncomfortable in terms of visual fatigue and symptoms like headache, motion sickness, or eyestrain. Eight participants considered some of the stimuli to be more difficult than others. It seems that this is a result of the different depth distances between the objects. Four participants stated that the very front positions of the squares were more difficult and one pointed out that the stimuli with large distances from the screen were more demanding. Overall, the participants rated the task as not arduous.

Table 5.1: Test statistics of the TCT for the tested depth locations using a Holm-Bonferroni correction.

Test Condition	**Wilcoxon Test**	**Corrected α**	**Significance**
-40 Px vs. -20 Px	$Z = -3.245; p = 0.001$	$\alpha = 0.006$	**sig.**
-40 Px vs. 0 Px	$Z = -2.678; p = 0.007$	$\alpha = 0.008$	**sig.**
-40 Px vs. 20 Px	$Z = -3.724; p < 0.001$	$\alpha = 0.005$	**sig.**
-40 Px vs. 40 Px	$Z = -3.419; p = 0.001$	$\alpha = 0.006$	**sig.**
-20 Px vs. 0 Px	$Z = -1.894; p = 0.058$	$\alpha = 0.013$	n.s.
-20 Px vs. 20 Px	$Z = -3.114; p = 0.002$	$\alpha = 0.007$	**sig.**
-20 Px vs. 40 Px	$Z = -1.241; p = 0.215$	$\alpha = 0.025$	n.s.
0 Px vs. 20 Px	$Z = -0.414; p = 0.679$	$\alpha = 0.05$	n.s.
0 Px vs. 40 Px	$Z = -1.459; p = 0.145$	$\alpha = 0.017$	n.s.
20 Px vs. 40 Px	$Z = -2.461; p = 0.014$	$\alpha = 0.01$	n.s.

5.1.4 Discussion

The results show an overall low error rate when solving the task. This is a strong indicator that binocular disparity enables an accurate depth perception – even if other depth cues are excluded such as relative size. Thus, a correct depth impression can be achieved without the need to extremely shrink the content, which would make it unrecognizable or unreadable. In addition, objects that are presented in the foreground do not need to become very large and thus occupy valuable space for visualizing further information or occluding other objects on the screen. This finding is valuable for designing UIs particularly for small display sizes since the extreme use of relative size is not necessary.

The low error rate suggests that small depth differences can be accurately recognized. Additionally, as the z-distance between the objects increases participant's information processing occurs faster. Our findings suggest that 3 pixels parallax difference (corresponding to 2.7 arc-min angular disparity at screen depth) is a threshold beyond which no more significant decrease in TCT is expected. Yeh and Silverstein [265] identified a mean error of 2.2 arc-min for judging stereoscopic depth. However, their finding is solely based on judgment accuracy while our outcomes are based on accuracy as well as task completion time.

Within the comfort zone, a number of indications suggests that the users have no problem solving the tasks with high accuracy. This is reflected by the low error rates and the fact that the tasks were rated as neither being demanding, nor uncomfortable, nor as causing visual fatigue. However, the findings suggest that the parallax limits of the comfort zone should be narrowed down to improve the quick perception of the depth layout. This outcome concerns positions in front of the screen rather than locations behind the screen plane. In general, our results show that TCTs are significantly higher for negative parallaxes than for positive parallaxes. Hence, it is beneficial to present information behind the screen while front positions should be applied carefully. Based on our data, we recommend to avoid negative parallaxes exceeding 20 pixels (17.9 arc-min). No statistical differences could be shown within the area of 0 up to 40 pixels of positive parallax (35.9 arc-min angular disparity), while the TCT tends to be lowest for 20 pixel positive parallax (17.9 arc-min angular disparity). Though we did not test this, we assume that positive parallaxes beyond the comfort zone increase TCTs. Figure 5.2 depicts this tendency of the TCT behind the screen. In consequence, we recommend to display information within a depth range of 17.9 arc-min negative parallax and 35.9 arc-min positive parallax, while positions in front of the screen should be applied carefully.

5.2 Structuring Information using Depth

The previous section shows that there are depth ranges within the comfort zone that maximize depth perception based on stereoscopy. We assume that we can use those areas to structure user interface elements via depth. Considering the application of automotive user interfaces, we envision navigation cues to be presented in an easy-to-understand manner by clearly communicating the distance to the next turn action. Moreover, warning information on the car status, for example that a door is open or that refueling is required soon can be displayed further to the front in order to attract the user's attention. At the same time, currently less important information could be displayed further in the back.

We conducted a user study to evaluate how information can be structured and grouped in a 3D layered user interface. In particular, we are interested in user performance when identifying grouped objects on one depth plane while several other (distractor) layers are present. We investigate how the number of layers, the distance between those layers, and the x- and y-distance between grouped objects impact TCTs and error rates for a search task incorporating depth. For

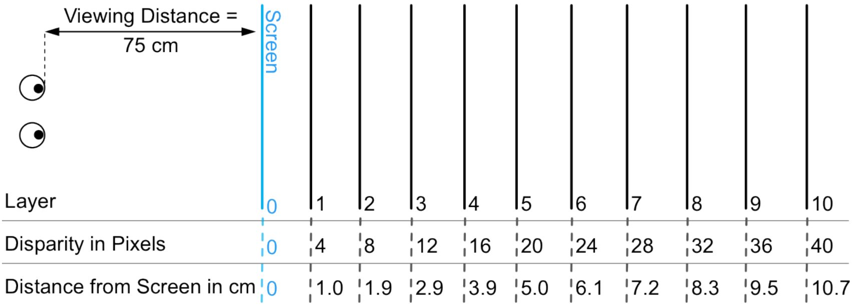

Figure 5.3: Layer positions applied in the user study. The distances between the screen layer and each depth layer are given in pixels and cm.

this search task, participants have to identify two related objects among several distractor objects. The relation between the objects is defined by their depth position, meaning that objects on one depth layer belong to one group. This approach is based on the one of Yeh and Silverstein [265]. They used this task to investigate the accuracy of perceiving stereoscopic depth while we study the use of S3D for structuring elements in space.

We investigate the following hypotheses:

- H1: Smaller numbers of depth layers increases user performance in identifying grouped objects via depth.
- H2: Grouping objects additionally via the x and y axis increases user performance in identifying grouped objects in 3D depth.
- H3: Increasing the distance between depth layers increases user performance in identifying grouped objects via depth.

5.2.1 Apparatus and Study Design

For presenting information layers with different depth positions, we again employ the prototype already used for assessing the comfort zone (cf., Section 4.2) and user performance in perceiving stereoscopic depth (cf., Section 5.1). As a depth range we use positive parallaxes up to 40 pixels and as a minimum distance between two depth layers we use 4 pixels in accordance with our prior findings. As negative parallaxes should be applied well-considered, we deliberately investigate

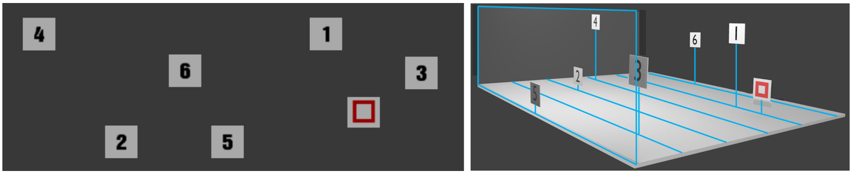

Figure 5.4: The used task requires stereoscopy to identify the target object. The left picture depicts the stimulus in a monoscopic visualization. The right picture shows a perspective side-view of the scene, which clarifies the depth relations. In this example, the numbered squares occupy six layers while the reference object is located at the same depth layer as object 1.

depth locations behind and not in front of the screen layer for this study. Figure 5.3 visualizes the examined positions for the depth layers. The values are calculated with respect to our setup (pixel pitch = 0.196; viewing distance = 750 mm).

The participants had to solve search tasks based on stereoscopic depth. Hence, we gathered insights into user performance when deciding on depth relationships between objects presented by the 3D display. A number of squares labeled with numbers were placed on different depth layers. In addition, a reference object showing a red square was positioned on the same depth layer as one of the numbered objects (we refer to this as the target object). The task for the participant was then to find the object placed on the same depth layer as the reference object. All objects were squares with a height and width of 90 pixels. Note, that due to the lack of monocular depth cues it was not possible to identify the target object in a monoscopic presentation of the stimulus (cf., Figure 5.4). Between two tasks the participants had to solve a distractor task that requires them to focus cognitively and visually on the distractor display. We used the same distractor tasks as presented in the last Section 5.1. The study was designed as a repeated measures experiment. We altered three independent variables:

- **Depth Layers:** We expected that the number of depth layers impacts user performance. Therefore, we tested the impact of 4, 6, and 8 depth layers.
- **XY-Distance:** Based on the law of proximity, we expected effects on user performance for varying x- and y-distances between the target and reference object. We investigated small (i.e., 5%-15% of the screen's diagonal), medium (i.e., 35% - 45%), and large distances (i.e., 65% - 75%) for this study.

- **Z-Distance:** The distance between two layers can be maximal (i.e., the layers are linearly distributed within the available depth budget ranging from 0 pixels to 40 pixels positive parallax) or minimal (i.e., the layers are seperated by a distance of 4 pixels with the first layer starting at the screen plane).

Beside these independent variables, the depth position of target and reference objects can have a potential influence on user performance. Hence, we tested every possible layer position for target and reference square over all conditions. This results in (4 layers * 3 xy-distances * 2 z-distances) + (6 layers *3 xy-distcances * 2 z-distances) + (8 layers * 3 xy-distances * 2 z-distances) = 108 tasks that every user has to solve. We grouped the conditions by blocks of depth layers. To avoid sequence effects we counterbalanced the presentation of these blocks resulting in 6 groups. The order of the xy- and z-distance conditions was randomized for each block. We measured TCT and error rates for solving the tasks. Beside these objective measurements, the users rated the perceived difficulty of the task.

5.2.2 Experimental Setup and Procedure

The experimental setup as well as the study procedure are similar to the study presented in the previous Section (cf., Section 5.1) except for the applied tasks. After a training session (12 tasks), the participant started with the first task of the respective depth layer block by pressing the space key on the provided keyboard. After the participants detected the target object, they pushed the space key and the stimulus on the 3D display disappeared. Then they told the examiner the number shown on the target object. The time difference between the keystrokes was measured as TCT. Next, the participant performed the distraction task. This procedure was repeated for all three depth layer blocks. After each block, the participants completed a questionnaire evaluating the difficulty of the task as well as discomfort in terms of headache, eye-strain, nausea, and dizziness. The participants rated these items on a seven-point Likert scale, ranging from very low (1) to very high (7).

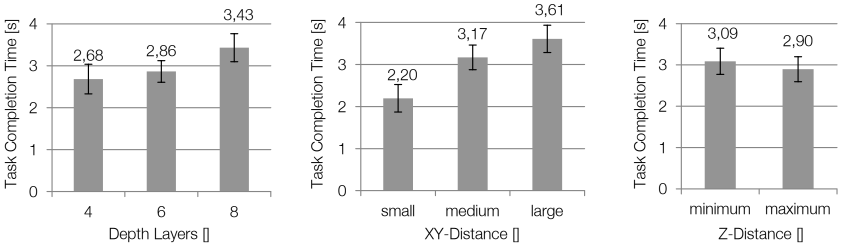

Figure 5.5: TCT mean values and standard errors as error bars for the three independent variables: depth layers, xy-distance, and z-distance.

5.2.3 Results

In total, 30 participants (6 female, 24 male) aged between 20 and 53 years ($M = 29.0$, $SD = 6.9$) took part in this study. All participants had normal or corrected to normal visual acuity and passed the stereo vision test.

Task Completion Time

Figure 5.5 shows plots for the TCT with regard to depth layers, xy-distances, and, z-distances. The diagrams clearly depict an increase of the TCT for an increased number of depth layers, higher xy-distances, and a smaller z-distance. A three-way ANOVA with repeated measures reveals statistically significant differences for TCT concerning the number of depth layers, $F(2,58) = 13.877$, $p < .001$, $r = .548$, the xy-distance between target and reference object, $F(2,58) = 59.926$, $p < .001$, $r = .814$, and the z-distance between depth layers, $F(1,29) = 4.361$, $p = .046$, $r = .317$. We used pairwise t-tests with Bonferroni corrections for post-hoc analysis. For the number of depth layers, the t-tests reveal statistically significant effects between 4 and 8, $T(29) = -5.564$, $p < .001$, as well as 6 and 8 layers, $T(29) = -4.242$, $p < .001$. The comparison of 4 with 6 layers is not statistically significant, $T(29) = -1.047$, $p = .911$. Concerning the xy-distances, the pairwise t-tests reveal significant differences between all distances, all $p \leq .001$. Beside the main effects, the ANOVA shows significant interaction effects for amount of layers * xy-distance, $F(2.054, 59.567) = 3.939$, $p = .024$, $r = 0.299$ (Greenhouse-Geisser), and xy-distance * z-distance, $F(2,58) = 3.585$, $p = .034$, $r = 0.282$, but not for depth layers * z-distance, $F(2,58) = .227$, $p = .798$, as well as depth layers * xy-distance * z-distance, $F(4,116) = .857$, $p = .458$. The plots in Figure 5.6 depict the interactions. The middle plot shows

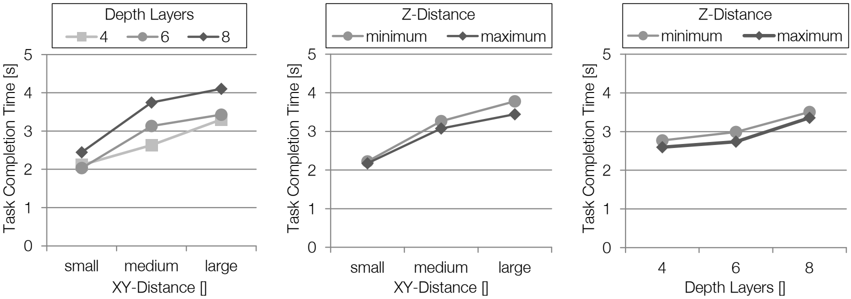

Figure 5.6: Plots depicting the mean values for the TCT of the following interactions: depth layers * xy-distance (right), xy-distance * z-distance (middle), depth layers * z-distance (left).

that a maximum depth difference between the layers lowers the increase of the TCT due to higher xy-distances.

Error Rate

Figure 5.7 depicts mean and standard errors of the error rate for depth layers, xy-distances, and, z-distances. Analyzing the error rate, a repeated measures ANOVA shows statistically significant differences for the number of depth layers, $F(2,58) = 20.486$, $p < .001$, $r = .628$, xy-distance, $F(1.687,48.913) = 49.033$, $p < .001$, $r = .785$ (Huynh-Feldt), and z-distance, $F(1,29) = 30.230$, $p < .001$, $r = .702$. In accordance with the results of the TCT, pairwise t-tests with Bonferroni corrections show statistically significant differences for comparing 4 with 8, $T(29) = 6.475$, $p \leq .001$, and 6 with 8 depth layers, $T(29) = 4.090$, $p \leq .001$.

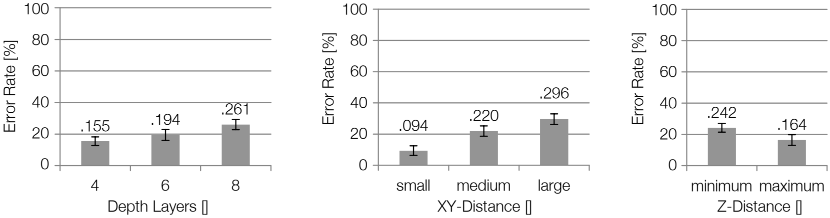

Figure 5.7: Mean values and standard errors as error bars for the error rate of solving the tasks in regard to the three independent variables depth layers, xy-distance, and z-distance.

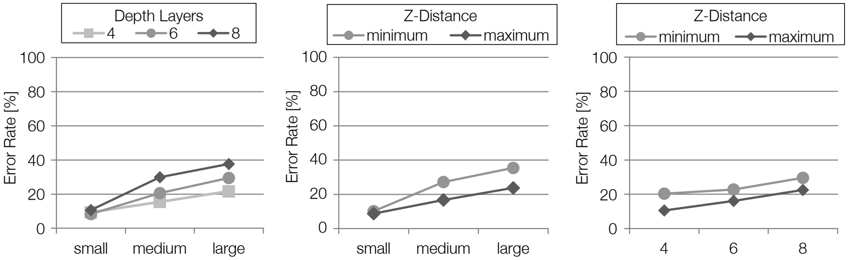

Figure 5.8: The plots depict the mean values for the error rates of the following interactions: depth layers * xy-distance (right), xy-distance * z-distance (middle), depth layers * z-distance (left).

Again, comparing the use of 4 and 6 depth layers reveals no statistical significance, $T(29) = 2.263$, $p = .094$. Moreover, all pairwise comparisons of xy-distances are statistically significant, $p < .001$.

The conducted ANOVA shows significant interaction effects for depth layers * xy-distance, $F(4,116) = 5.030$, $p = .001$, $r = .344$, and xy-distance * z-distance, $F(1.677,48.623) = 7.240$, $p = .003$, $r = .415$ (Huynh-Feldt) but not for depth layers * z-distance, $F(2,58) = .572$, $p = .593$, and depth layers * xy-distance * z-distance, $F(3.425,99.316) = .409$, $p = .773$ (Huynh-Feldt). Figure 5.8 depicts the interaction of the independent variables. The left plot shows that the error rate is similar for the investigated depth layers for a low xy-distance. Using six and eight depth levels the error rate increases more extremely for higher xy-distances than for 4 depth layers. The middle plot suggests that the z-distance does not matter for a low xy-distance. Looking at a medium or large xy-distance the minimum z-distance increases the error rate drastically in comparison to the maximum z-distance.

Subjective Ratings

The participants rated the perceived difficulty of the depth-related search task as well as visual discomfort after each depth layer block. The descriptive statistics of the rating are depicted in Figure 5.9. The participants rated the tasks with a higher number of depth layers as more difficult. A Friedman test reveals statistically significant differences for the subjectively rated difficulty regarding the variation of depth layers, $X^2(2) = 13.640$, $p = .001$. Pairwise comparisons using Wilcoxon tests show significances between 4 ($M = 3.567$, $SD = 1.612$) and 6 layers ($M = 4.067$, $SD = 1.388$), $p = .039$, as well as between 4 and 8 layers ($M = 4.500$, $SD = 1.614$), $p = .006$. In general, participants state that it is easier to solve the task if the target and reference pair is placed at the foremost or rearmost depth layer. Furthermore, the task is perceived as easier if no objects are located between the target and reference layer in terms of the object's x- and y-position on the screen. Some participants explained this issue in more detail: Since distractor objects had random x and y positions it was sometimes the case that the objects' arrangement exhibits a comprehensible structure through x, y, and z dimension, for example, a straight or curved line reaching from the foremost layer to the back. The participants mentioned that those structures facilitated the search task. The tests show no statistically significant influences concerning the number of depth layers on visual discomfort in terms of headache, $X^2(2) = .333, p = .846$, dizziness, $X^2(2) < .001, p = 1.000$, nausea, $X^2(2) = 2.000, p = .368$, and eye strain, $X^2(2) = 4.955, p = .084$.

As a further investigation, we analyzed the first, second, and third measurement of the subjective ratings. In this way, we can determine if a longer usage of the 3D display impacts the difficulty as well as viewing comfort. The right diagram of Figure 5.9 depicts that the difficulty decreases after each test block. However, this result is not statistically significant, $X^2(2) = 3.798, p = .150$. The items measuring visual discomfort show similar ratings for each run, while the items headache, dizziness, and eye strain are even rated slightly lower after the first measurement. Nevertheless, Friedman tests reveal no significant effects for headache, $X^2(2) = 1.513, p = .368$, dizziness, $X^2(2) < 6.000, p = .05$, nausea, $X^2(2) = 2.000, p = .368$, and eye strain, $X^2(2) = 1.682, p = .431$.

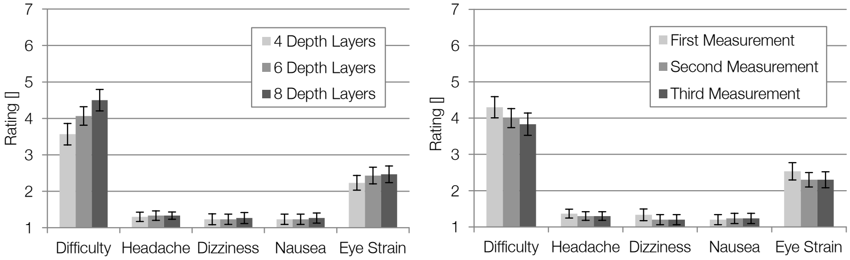

Figure 5.9: Means and standard errors of the subjective rating. The left diagram depicts the rating due to the depth level while the right shows the rating with respect to the order of the measurements

5.2.4 Discussion

The presented study investigates the influence of the number of depth layers, their differences in depth as well as the influence of xy-distances for grouping and structuring information on depth layers. The results let us derive answers on the prior defined hypotheses and implications which we discuss in the following.

Information Layers

Our results show that an increasing number of depth layers lowers user performance in terms of TCT and error rate. The subjective ratings on the task difficulty support this finding. As a result, we can accept hypothesis H1. An explanation for this finding is provided by the Hick-Hyman law [92] (increasing the number of choices will increase the decision time) as well as the feature integration theory of Treisman [235] (increasing distractor objects increase search time for a serial search). As a result, the applied task requires a serial search. While the findings of Nakayma and Silverman [162] suggest that two depth layers can be searched in parallel our findings demonstrate that increasing the amount of layers hampers user performance for complex search tasks in S3D depth.

Our study shows that the decrease in performance is not statistically significant between 4 and 6 layers, although we observed a minimal performance decline. Hence, we assume that six information layers are still suitable for distributing information in 3D space, while 8 layers decrease user performance significantly. Based on these results, we recommend a maximum of 6 information layers.

Proximity in the Third Dimension

As our findings suggest, the xy-distance between objects plays a major role for grouping information via depth. As user performance significantly declines for an increasing xy-distance between target and reference object, we accept hypothesis H2. Besides a proper depth layer position of user interface elements, x- and y-locations have to be considered carefully. In general, the Gestalt psychology provides laws for grouping elements through specific characteristics. The law of proximity explains the performance reduction for increasing xy-distances and proves valid for the examined depth layers.

Moreover, we found that the law of proximity is also valid for the z-dimension. Maximizing the distance between depth layers within the comfort zone improves user performance. Hence, our study also confirms hypothesis H3. Nevertheless, this effect is absent for small x- and y-distances between grouped objects.

3D Exposure and Discomfort

In general, the prolonged exposure to 3D content increases visual discomfort [94, 129]. However, our data reveals that the prolonged use of our prototype does not increase symptoms such as headache, dizziness, nausea, and eye-strain. In contrast, the symptoms tend to decline for a longer usage. Thus, the chosen depth range allows a comfortable viewing experience and validates the prior defined comfort zone threshold of 35.9 arc-min for positive parallaxes.

5.2.5 Limitations

In this and the previously described study (cf., Section 5.1), we explored user performance in perceiving S3D depth. To address various applications areas and maximize internal validity, we used rather abstract tasks (e.g., finding objects on the same depth level), used abstract content, and kept object parameters (e.g., color, size, and position) constant. As our results show, the chosen tasks require TCTs longer than 2 seconds. In fact, these artificial tasks are not directly applicable on most real world applications. For example, automotive UIs require tasks that are interruptible and do not need immediate responses for infotainment related applications. We used these abstract tasks to gain insights into the effect of spatial structuring using S3D rather than evaluating a typical task that is found in real world applications.

5.3 Choosing Depth Cues

In order to get closer to the application of S3D for automotive UIs, we deliberately opted to exploratory investigate the application of different depth cues for automotive IC concepts. Today, there are no commonly agreed guidelines and principles as to how novel digital ICs should be designed to optimally support both the driving task and the user experience. In this section, we present the influence of different display layout concepts and their spatial representation on the user experience. Therefore, we developed three display layout concepts, that differ in their appearance from well-known and classic (i.e., gauges for speed and rpm) to novel and modern. For generating a 3D impression of the concepts, we implemented a monoscopic representation, which allows to add motion parallax and S3D as depth cues. 12 participants compared the developed designs due to all permutations of the investigated depth cues. The results show that stereoscopy increases the perceived quality of the display while motion parallax should be applied carefully to avoid that the UI appears too crowded.

5.3.1 Instrument Cluster Concepts

We created three different IC designs for a stereoscopic display. In order to use the 3D effect well-considered, we followed the outcomes of our previous studies concerning the comfort zone (cf., Section 4.2) and the user performance in depth (cf., Section 5.1 and 5.2). The first design represents a classic design as known from cars without digital displays (cf., Figure 5.10). The second design is a modern version with abstract representations of each part of the interface (cf., Figure 5.11). The third design does not rely on the circular instruments but rather uses planes to visualize the information (cf., Figure 5.12).

To make the concepts comparable, we designed them to display the same types of information. The concepts depict the current speed, rpm, oil temperature, and fuel level. Moreover status information is displayed as the time of day, the outside temperature, trip odometer, and odometer. As driving assistance function each concept depicts ACC with the detected preceding vehicle as well as the adjusted distance. In addition, each design contains a menu structure with four entries (i.e., fuel efficiency, navigation, communication, music). Note, that the menu is located roughly at the same position in all layouts to ensure comparability while interacting. To control the menu, four buttons on the steering wheel are used, namely, *back*, *select*, *left* and *right*. If no menu is active, the *left* and *right* buttons are used to cycle between the options (i.e., fuel, phone, music, or navigation). When pressing *select* the highlighted menu is activated. With an active menu, the *left* and *right* buttons are used to navigate through its functions. The *select* button is then used to perform an action (e.g., reset trip odometer or call the selected contact). To visually support the activation of a menu, the object containing the menu moves towards the user upon entering it. In the following, we provide a detailed description of the three designs.

Classic

The first design transfers the look of analogue gauges into a digital display (cf., Figure 5.10). The choice of colors and materials intends to mimic high-class real world materials such as chrome for the gauge rings, carbon fiber for the background and red illuminated glass for the pointers. There are five gauges – three small ones for the fuel level on the left, oil temperature on the right, and

Figure 5.10: Classic design as 2D presentation.

menu information in the middle. The two larger ones show the speed and rpm. The speed gauge contains the menu icons while the rpm gauge holds the digit of the current gear. The ACC icon is displayed above the menu gauge.

Circles

Maintaining the association with analogue gauges, the *Circles* design displays speed and rpm by filling the area between the inner and outer circle of the tilted blue wire-framed gauges clockwise (cf., Figure 5.11). Tank level and oil temperature are visualized through narrower areas, filling counterclockwise. The left and right gauges contain a numeric display of current speed, respectively, rpm and current gear, while the upper semicircle holds the ACC and turn indicator icons. The lower circle serves as indicator for the currently selected menu of

Figure 5.11: 2D presentation of the design *Circles*.

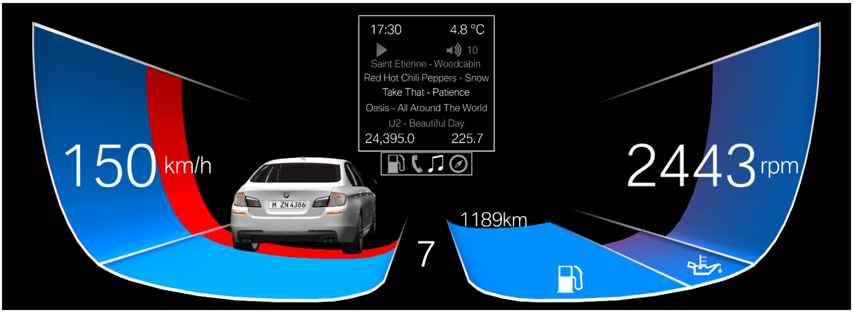

Figure 5.12: 2D presentation of the design *Lines*.

the car computer and contains time of day, temperature, and odometers. When selecting another one of the four menus, the circle rotates by 90 degrees. The center cube holds those four menus on its four lateral sides and also rotates by 90 degrees, if another menu is selected.

Lines

The third design (cf., Figure 5.12) visualizes speed and revolutions in horizontal areas, filling from front to back (i.e., expanding in the third dimension). The display is divided into two shells, the one on the left showing speed, the right one showing fuel level, oil temperature, rpm, as well as a gear digit in the lower middle. A small bar in the center of the IC contains the menu options and a square holding the previously activated menu. Instead of an ACC icon, there is a 3D car model, depicting the distance to the vehicle ahead in the left shell.

5.3.2 Apparatus and Study Setup

We implemented the concepts in Unity[23] using C# as script language. The stereoscopic visualization was achieved by using Nvidia 3D Vision on an Asus G75VW notebook, whose display supports the necessary refresh rate of 120Hz for shutter glasses. For implementing motion parallax, TrackIR[24] was used, interfacing with Unity3D through the Unity-TrackIR Plugin. TrackIR consists of

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[23] https://unity3d.com/, last accessed October 19, 2015.

[24] http://www.trackir.fr/, last accessed October 7, 2015.

Figure 5.13: The participants used a Logitech steering wheel and pedals to interact with the IC concepts.

an USB device with infrared (IR) LEDs, a camera to record IR reflections and a target providing three semicircular reflecting areas in a set distance. The target was attached to a baseball cap, which had to be worn by each participant during the experiment and thus enabled the software to track their head in 6 degrees of freedom.

The study setup consisted of a car seat with a Logitech steering wheel and pedals (cf., Figure 5.13). The shutter notebook displaying the IC was placed on a table behind the steering wheel. Beside the cap for the head tracking, the participants had to wear shutter glasses for perceiving the S3D effect. To achieve comparable conditions, the participants wore this equipment for each test condition.

5.3.3 Study Design and Procedure

After participants arrived in the lab, we first calibrated the TrackIR system. Then we introduced them to the input device (i.e., buttons on the steering wheel). In total, we had twelve conditions: three designs (*Classic*, *Circles*, and *Lines*) with the four depth cue settings (*monoscopic (2D)*, *motion parallax (2DMP)*, *S3D*, and *S3D with motion parallax (S3DMP)*). The order of the conditions varied for each participant using latin square. In each condition, we presented five different tasks

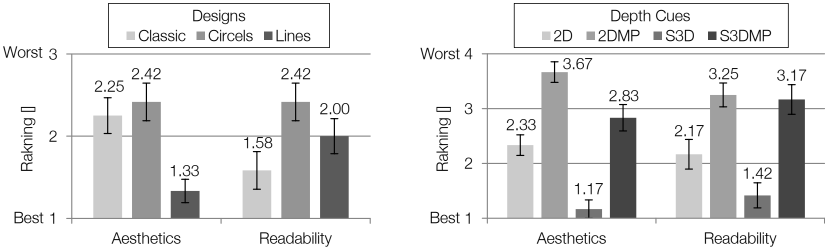

Figure 5.14: Bar charts of means and standard errors of the ranks pertaining readability and aesthetics for the tested designs (left) and depth cues (right). Note, the lower the bars the better the ranking.

(e.g., selecting a song or switching the gears). After the participants conducted the tasks we gave them time to playfully explore the interface. Each participant performed the five tasks with all twelve conditions. After each condition, the participant filled in an AttrakDiff mini questionnaire [90]. After all conditions, the participants ranked the designs from one (best) to three (worst) and the depth cue settings from one (best) to four (worst) regarding aesthetics and readability.

5.3.4 Results

We recruited 12 participants (4 female, 8 male) aged from 22 to 32 years ($M = 25.0$, $SD = 3.1$) through our internal mailing list. All of them were familiar with automotive UI development, its requirements, and challenges.

Readability and Aesthetics

The classic version reveals the best rankings for readability while the lines design receives the best rankings regarding aesthetics. In general, the *S3D* versions received the best rankings (cf., Figure 5.14) for both, readability and aesthetics. Regarding aesthetics, a Friedman ANOVA shows statistically significant differences for the designs, $X^2(2,12) = 8.2$, $p < .017$, as well as the depth cues, $X^2(3,12) = 23.6$, $p < .001$. We use Wilcoxon tests with Bonferroni corrections for follow up pairwise comparisons. The Wilcoxon tests show significant differences comparing the designs *Lines* with *Circles*, $Z = -2.5$, $p = .012$, $r = -.51$, while the other comparisons of the tested designs are not significant. Regarding the used depth cues, *2DMP* is rated significantly worse than *2D*, $Z = -3.2$, $p = .001$, $r = -.65$, and *S3D*, $Z = -3.1$, $p = .002$, $r = -.64$. In addition, *S3D*

Table 5.2: Mean and standard deviations for each test conditions of the three dimensions of the AttrakDiff.

Design	**Cues**	**PQ**	**HQ**	**ATTR**
Classic	2D	$M = 5.333, SD = 0.989$	$M = 4.271, SD = 1.031$	$M = 5.042, SD = 1.010$
	2DMP	$M = 4.417, SD = 1.371$	$M = 4.146, SD = 1.031$	$M = 4.375\ SD = 1.432$
	S3D	$M = 5.604, SD = 0.801$	$M = 4.979, SD = 1.316$	$M = 5.375, SD = 1.131$
	S3DMP	$M = 4.688, SD = 1.149$	$M = 4.542, SD = 1.091$	$M = 4.708, SD = 1.157$
Circles	2D	$M = 4.917, SD = 1.135$	$M = 5.063, SD = 0.755$	$M = 5.000, SD = 0.905$
	2DMP	$M = 4.229, SD = 1.420$	$M = 4.958, SD = 0.922$	$M = 4.458, SD = 1.453$
	S3D	$M = 5.083, SD = 0.929$	$M = 5.250, SD = 0.833$	$M = 5.417, SD = 0.900$
	S3DMP	$M = 3.979, SD = 1.494$	$M = 5.104, SD = 0.876$	$M = 4.292, SD = 1.322$
Lines	2D	$M = 5.062, SD = 1.129$	$M = 5.125, SD = 0.420$	$M = 5.333, SD = 0.862$
	2DMP	$M = 4.729, SD = 1.506$	$M = 5.438, SD = 0.650$	$M = 5.208, SD = 1.117$
	S3D	$M = 5.542, SD = 0.897$	$M = 5.750, SD = 0.511$	$M = 6.042, SD = 0.690$
	S3DMP	$M = 4.813, SD = 1.127$	$M = 5.583, SD = 0.925$	$M = 5.375, SD = 1.227$

is ranked significantly better than *S3DMP*, $Z = -3.1$, $p = .002$, $r = -.64$. The other pairwise comparisons of the depth cue conditions are not significant.

The ranking pertaining readability is not statistically significant for the designs, $X^2(2,12) = 4.2$, $p = .125$, but for the depth cues, $X^2(3,12) = 16.5$, $p < .001$. Pairwise Wilcoxon tests show that *S3D* is significantly ranked better than *2DMP*, $Z = -2.8$, $p = .005$, $r = -.57$, and *S3DMP*, $Z = -2.7$, $p = .008$, $r = -.54$. These results clearly show that participants do not like the motion parallax depth cue in regard to aesthetics and readability.

AttrakDiff

A summary of the means and standard deviations is shown in Table 5.2. Figure 5.15 depicts the scores for the tested designs and depth cues. The designs *Classic* and *Lines* shows the best scores for PQ, while *Lines* is rated best for HQ and ATTR. The *S3D* version received the highest scores in all dimensions.

For PQ, the ANOVA shows statistically significant differences for the depth cues, $F(3,33) = 9.059$, $p = .001$, $\eta^2 = .462$, but not for the designs, $F(2,22) = 1.274$, $p = .300$, and the interaction depth cues * design, $F(6,66) = 1.091$, $p = .377$. A pairwise comparisons of the depth cues conditions, using LSD, shows that PQ for *2D* was rated significantly higher than *2DMP*, $p = .037$ and *S3DMP*, $p = .03$, but significantly lower compared to *S3D*, $p = .039$. Moreover, the PQ is significantly lower for *2DMP* than *S3D*, $p < .003$, and *S3D* has a significant higher PQ than *S3DMP*, $p = .002$. In regard to the dimension HQ, the ANOVA

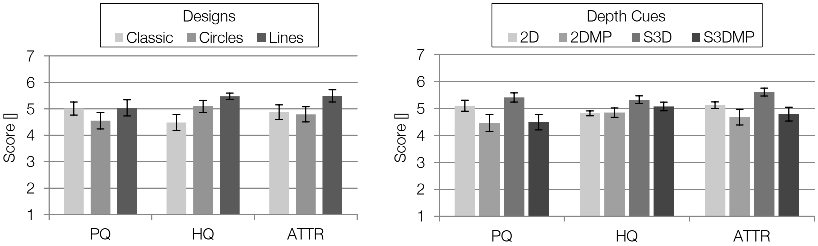

Figure 5.15: Bar charts of means and standard errors of the AttrakDiff's dimensions PQ, HQ, and ATTR for the tested designs (left) and depth cues (right).

shows statistically significant differences for the depth cues, $F(3,33) = 5.012$, $p < .006$, $\eta^2 = .313$, as well as for the tested designs, $F(2,22) = 4.219$, $p = .028$, $\eta^2 = .277$, but not for their interaction, $F(6,66) = 2.102$, $p = .065$. LSD post-hoc tests reveal statistically significant differences for comparing the designs *Classic* with *Lines*, $p < .015$. Regarding the tested depth cues, we found statistical significances comparing *2D* with *S3D*, $p < .002$, and *2DMP* with *S3D* $p = .026$. Analyzing ATTR, the ANOVA shows statistically significant results for depth cues, $F(3,33) = 6.397$, $p = .002$, $\eta^2 = .368$, but not for the designs, $F(2,22) = 2.214$, $p = .133$ and the interaction, $F(6,66) = 1.154$, $p = .342$. LSD post-hoc tests show that *S3D* received statistically significant different ratings than *2D*, $p = .007$, *2DMP*, $p = .01$, and *S3DMP*, $p = .01$.

5.3.5 Discussion

In general, the results show that the depth cues have a stronger influence on the perceived quality of the IC than the tested design concepts. The *Classic* design has the advantage of a "well-known appearance" (n = 8), while the more modern design *Lines* offers a "novel and exciting experience" (n = 9). With regard to the tested depth cues, participants rated the stereoscopic version as more compelling, attractive, and usable than monoscopic presentations. They commented on the increased attractiveness generated through the depth impression as well as the "clarity of the element's arrangement in space" (n = 8). However, three participants mentioned the possible risk of distracting the driver from the driving task. In general, motion parallax performed poorly regarding the usefulness, attractiveness, and readability. This depth cue appears *too busy and nervous* (n = 11). Due to this characteristics, motion parallax is evaluated as too hazardous, pertaining visual and mental load for an automotive application. Nevertheless, the participants liked the intuitive zoom, that occurs when the viewer moves the head towards the display. Finally, classic designs raise a familiar and secure feeling and modern designs foster an exciting experience. However, the chosen depth cues visualizing the instruments have an even greater impact on the subjective quality. A well-considered use of S3D increases attractiveness and the perceived usability. In contrast, motion parallax evokes a nervous appearance of the interface.

5.4 Depth Perception in a 3D HUD

So far, this chapter describes the usage of depth to maximize the user performance as well as user experience in regard to an automotive IC. In contrast, this Section aims at investigating the usage of S3D for a HUD. We already investigated comfortable viewing zones for a HUD in the last chapter (cf., Section 4.3). We use those findings to study if S3D provides a proper depth perception for a see-through display. Augmenting the real world with stereoscopic projections allows to display virtual content at the same depth position as the augmented real world object. Hence, a navigation arrow can appear at the same distance where the next turn is located. Regarding related work, Swan et al. [229] investigated depth estimations in augmented environments using an optical see-through display. They found that distances up to 23 meters are commonly underestimated while higher distances are overestimated. The study of Swan et al. focused on a fixed projection distance. In contrast, we deliberately investigate the accuracy of judging the depth positions of real world objects for different projection distances. In a exploratory laboratory study, 25 participants used a virtual 3D object to estimate the depth of five different real world objects.

5.4.1 Apparatus and Study Design

We used a similar setup as in the study assessing the comfort zone. The emulator which is described in Section 4.3 showed a square of approximately 3.4 to 3.9° angular size with a number on it. The test environment was equipped with white shields having black marked edges. They were placed on pre-defined positions and carried black numbers. Figure 5.16 depicts the setup from the participants' point of view. We applied a perceptual matching task as described by Swan et al. [229]. Thus, the participants' task was to adjust the depth of the virtual object to the depth of the real world shield with the respective number. The participants

Figure 5.16: The setup of the depth judgment study shows a numbered virtual object through a see-through display and several real world shields.

used a game pad to manipulate the position of the numbered square in discrete steps of 5 cm. If the participants perceived the virtual object at the same depth as the respective shield, they confirmed the depth position by pressing a button on the game pad. According to the study assessing the comfort zone, we refer to the projection distance as VSD and the distance between the viewer and the virtual image as VID.

The study was designed as a repeated measure experiment with two independent variables.

- **VSD:** We tested the depth judgment accuracy for different VSDs at 3 m, 5 m, and 8 m.
- **Shield Position:** The participants judged the depth of five different shield positions for each VSD. The shields have a distance from the viewer of 2.4 m, 5.5 m, 8.5 m, 12 m, and 16 m.

Each test session was divided into three parts, one for each VSD level. We counterbalanced the order of the VSDs by dividing our test sample in $3! = 6$ groups. Every participant adjusted the depth position of the virtual image four

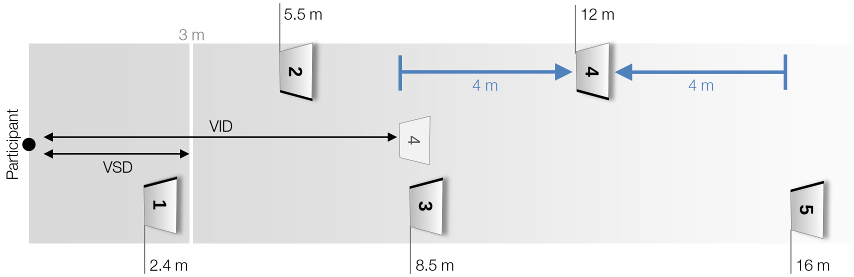

Figure 5.17: Top view of the study setup for a VSD of 3 m. The participants adjusted the virtual object to its corresponding shield (in this case shield 4). The initial position of the virtual object is either 4 m in front or 4 m behind the respective shield.

times for each VSD and shield combination. Thereby, the initial position of the virtual object was 4 m in front or behind the shield which had to be judged (cf., Figure 5.17) except for the first two shields. Here, the virtual image appeared at a VID of 2 m for approaching them from the front to avoid excessive negative parallaxes. Each shield was approached twice from the front and twice from the back in each test condition. This results in $4 * 5 = 20$ depth judgments for each VSD level. The sequence of the 20 tasks for one VSD part was randomized. In total, one participant provided $20 * 3 = 60$ depth estimations. As dependent variable we measured the absolute offset between the adjusted VID position of the virtual square and the respective real world shield. In the remainder, we refer to this value as the absolute judgment error.

5.4.2 Experimental Setup and Procedure

The initial assessment of demographic data, the measurement of the participant's eye distance, and the preceding vision tests were performed analog to the study assessing the comfort zone for a 3D HUD (cf., Section 4.3). Then, the participants acquainted with the system and the task during a training run. After that, two test runs for each VSD occurred. Each run included the judgment of all five shield positions from both directions in respect to the study design. A schematic overview of the setup is shown in Figure 5.17. The setup had to be rearranged to realize the different VSDs. Different additional light sources were used in order to illuminate the shields and their numbers sufficiently. We conducted an accompanying semi-structured interview about the effort and discomfort the participant felt using the 3D HUD and about the subjective degree of task difficulty.

Table 5.3: Means and standard deviations in brackets for the absolute depth judgment errors in meter.

Shield No	**VSD**			
	3 m	5 m	8 m	Overall
1	0.123 (0.254)	0.188 (0.347)	0.249 (0.454)	0.186 (0.339)
2	0.173 (0.095)	0.105 (0.063)	0.095 (0.049)	0.124 (0.049)
3	0.3850 (0.224)	0.199 (0.155)	0.192 (0.096)	0.259 (0.117)
4	0.760 (0.459)	0.383 (0.217)	0.256 (0.151)	0.466 (0.220)
5	1.444 (1.046)	0.731 (0.417)	0.467 (0.263)	0.881 (0.525)
Total	0.577 (0.337)	0.321 (0.145)	0.252 (0.138)	0.383 (0.506)

5.4.3 Results

In total, the results of 25 participants (7 female, 18 male) aged from 34 to 65 years ($M = 47$, $SD = 10$) were evaluated. All 25 participants had normal or corrected to normal vision and passed the RDS test. Table 5.3 and Figure 5.18 present the descriptive statistics of the absolute judgment error for the test conditions. The data show that the error increases for higher shield distances while it decreases for increasing VSDs. As Kolmogorov-Smirnov tests reveal that the data are

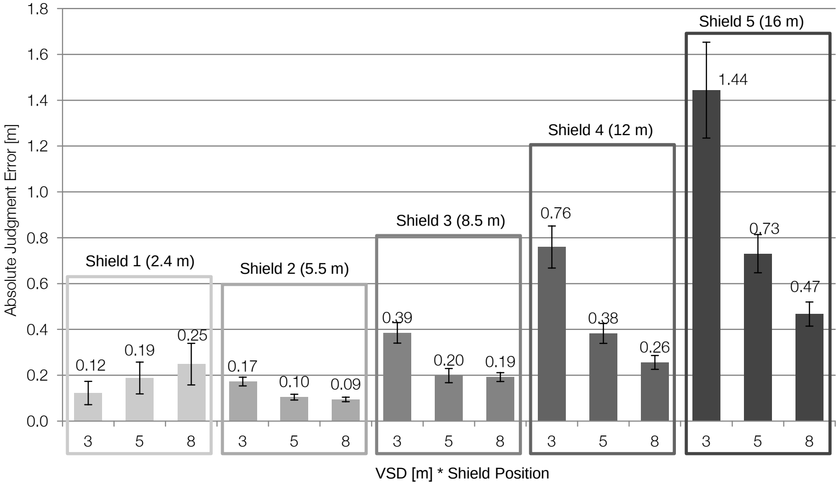

Figure 5.18: Means and standard errors for the absolute judgment error.

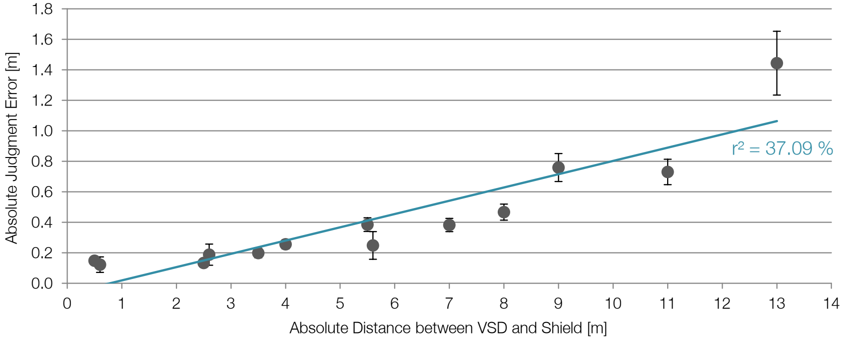

Figure 5.19: Means and standard errors depicting the correlation between the absolute depth judgment error and the distance between shield and VSD. The blue solid line shows a linear regression through all means.

not normally distributed we used Friedman and Wilcoxon tests with Bonferroni corrections to follow-up significant findings.

Comparing the shield positions a Friedman test shows that the accuracy of judging various real distances differs significantly, $X^2(4) = 70.237$, $p < .001$. Bonferroni corrected Wilcoxon tests show significant differences for all pairwise comparisons, $p < .005$, except for shield 1 vs. 2, $p = .119$, as well as for shield 1 vs. 3, $p = .016$. The different VSD levels provide significantly different accuracies for judging the shield positions as a Friedman test shows, $X^2(2) = 22.92$, $p < .001$. Wilcoxon tests with a Bonferroni corrected significance level reveal significant differences for all pairwise comparisons, $p < .005$. Figure 5.18, which directly pictures the absolute judgment error, implies that the accuracy of the judgment decreases with increasing VSD value for shield 1. For all other shields the effect occurs vice versa. This leads to the assumption that an increasing distance between shield and VSD impairs the accuracy of the depth judgment. Figure 5.19 represents the accuracy of the depth judgment based on the distance between the shields and VSDs. It shows that there is a strong correlation between the depth judgment accuracy and the distance between VSD and shield positions, $r = .609$, $p < .001$.

None of the participants mentioned symptoms of visual discomfort during the study. 93 % of the participants appreciated the use of stereoscopy for an automotive HUD. 34 % favored the VSD of 5 m for the depth judgment task, 28 % prioritized the 8 m VSD and 24 % a VSD of 3 m. In general, the participants stated that the depth judgment of closer shields profits from smaller VSDs while higher VSDs facilitate the judgment of shields farther away.

5.4.4 Discussion

In accordance to the findings of Swan et al. [229], our results indicate that higher distances between the real world object and the viewer decreases the depth judgment accuracy. This phenomenon is well known since binocular disparity works best at near distances while its effectiveness decreases in the distance [44].

Moreover, our results show that the accuracy of depth judgments depends on the VSD and the distance between VSD and real world object. In more detail, small VSDs allow for a better judgment of small distances while high VSDs improve the depth judgment for far distances. Just shield number 1 (2.4 m) allows for a better judgment for the smallest VSD (3 m). The correlation of judgment error and distance between VSD and shield position (cf., Figure 5.19) explains this effect. In consequence, higher parallaxes decrease the performance in judging depth. However, this result could have been influenced by inaccuracies in measuring the participants interocular distance which directly impacts the depth judgment error. However, we assume that possible measurement errors are normally distributed over the conditions and have no significant influence on our result.

Our study produced data that quantify the accuracy of depth judgments humans can achieve using a stereoscopic see-through display. These data provide a benchmark for the accuracy that software and hardware solutions need to observe in order to realize AR applications for stereoscopic see-through displays. In regard to an automotive HUD, we argue that it is important to augment the real world at far distances as well as near distances in order to clarify, for example, the moment of an upcoming navigation maneuver. In this case, the accuracy of the depth position becomes more important for closer distances. Among the tested VSDs, we identify a VSD between 5 and 8 m as promising for the case of a stereo HUD as it allows quite accurate judgments for near as well as far real world objects. For example, the judgment error for a real world object 16 m away from the viewer is 73 cm while close objects at a distance of 2.4 m involve inaccuracies of 19 cm on average for a VSD of 5 m. These values demonstrate that depth judgments solely based on the use of stereoscopy are highly accurate within the tested depth range. Nevertheless, accuracy decreases with increasing distance and the depth cue binocular disparity even does not provide sufficient depth information beyond 30 meters [71]. At those distances monocular depth cues such as occlusion, horizontal positions with regard to the horizon, and relative size can appropriately depict spatial relations between virtual content and the real world.

5.5 Summary: Design Principles

This chapter presents four laboratory studies evaluating human depth perception for stereoscopic displays. We aim at using depth to maximize both, user experience as well as user performance. Observing the parallax limits defining the comfort zone, we investigated how to use depth to structure information (cf., Section 5.1 and Section 5.2), how stereoscopic parameters affect depth perception (cf., Section 5.1 and Section 5.4) and which depth cues improve the subjective quality of the UI (cf., Section 5.3). Except evaluating the use of different depth cues, we kept the used tasks rather abstract. That allows us to formulate design principles that address various application areas. In the following, we outline these principles and present examples for an automotive application.

- **Choose negative parallaxes well-considered for near viewing displays.** For short viewing distances (ca. 750 mm), our study, presented in Section 5.1, reveals that TCTs are minimized for recognizing depth differences behind the screen plane. We suggest to display information with positive parallaxes while negative parallaxes (positions in front of the screen) have to be applied carefully for those display settings. The drop in user performance regarding TCT for negative parallaxes close to the comfort zone limit is remarkably high. Therefore, we recommend to reduce the depth budget that should be effectively used for information presentation prior defined by the comfort zone (36 arc-min angular disparity) to 18 arc-min in front of the screen. Nevertheless, we assume that there are categories of information that profit by showing them in front of the screen. In particular, this includes content that is displayed for a rather short period of time and needs the immediate attention of the user. For automotive applications, warnings and check controls are prominent examples for that kind of information and could benefit from a dedicated position in front of the screen.
- **Use stereoscopy to structure information.** Stereoscopic depth can be used to structure information, for example, due to its importance. Despite the fact that a lot of different depth cues exist, the studies of Section 5.1, 5.2, and 5.4 show that solely S3D is suitable for information representation even if occlusion or changes in size are neglected. For near viewing displays, we found that a minimum of 2.7 arc-min leads to significantly better TCTs when it comes to distinguishing two different depth levels. Moreover, positive parallaxes maximize the perception of depth relations between objects (cf., Section 5.1). This finding suggests that content which carries information of spatial and temporal aspects should be presented

behind the screen plane. For example, navigation cues can clarify their currentness by means of their distance to the screen plane. The findings of Section 5.2 demonstrate that the 3D space should be used as a whole to structure information. Hence, the designer has to take the horizontal as well as vertical position of objects into account beside the depth position. In addition, a maximum of six different depth layers should be used in order to avoid spatial clutter. In general, we argue that the screen plane should be used for permanent displays that have a high importance since this display area does not suffer from image distortions that might potentially hamper the readability (e.g., crosstalk). For instance, screen depth is an appropriate depth position for displaying speed in regard to an automotive IC.

- **Do not use motion parallax.** Section 5.3 presents different IC concepts to evaluate the impact of depth cues, namely motion parallax and stereoscopy on user experience and the perceived usability. The results show that motion parallax makes the interface hectic and, hence, decreases the readability as well as the attractiveness of the user interface. In contrast, adding stereoscopic depth to perspective visualizations increases the user experience and the perceived usability due to a more structured appearance of the displayed content. However, we evaluated the depth cues by means of a concrete application. Please be aware that other application areas can benefit from motion parallax, for example, virtual environments and AR applications.

- **Augment reality with stereoscopic content.** In Section 5.4 we investigated the accuracy of judging real world depth with virtual 3D objects using a stereoscopic see-through display. The results show that depth positions can be judged highly accurately. We found an average judgment error of 0.19 m for a real world object at 2.4 m and an average error of 0.88 m for a real world position of 16 m. This proves that stereoscopy fosters the tagging of real world objects within this depth range. Our results demonstrate that near projection distances (e.g., 3 m) improve the tagging of objects that are closer to the viewer (2-5 m) while higher projection distances (e.g., 8 m) improve the depth perception for more distant areas (12-16 m). In general, our results determine the requirements the picture generating unit and the optics of a 3D see-through display have to fulfill in order to maximize the quality and effectiveness of the stereoscopic visualization. For an automotive HUD we recommend the use of a VSD between 5 and 8 meters. This range constitutes a good trade-off for comfortably displaying driving information such as speed close to the driver and at the same time allows for a feasible augmentation of real world objects at farther positions.

In summary, the presented studies let us derive design principles that support the development of usable stereoscopic applications. Since our data are based on specific display technologies and viewing settings the principles need to be validated for a concrete application. Studies are required that increase external and ecological validity of the formulated design principles. Nevertheless, our studies show that UI developers have to take several parameters (e.g., viewing distance, comfort zone, amount of depth layers) into account when it comes to creating an application for a stereoscopic display. The next part introduces prototyping tools that aim at reducing the complexity of choosing appropriate parameters and should facilitate the development process for stereoscopic UIs.

IV

PROTOTYPING TOOLS

OUTLINE

Prototyping is an essential aspect of user-centered design in order to exchange and evaluate ideas in every stage of the development process. This part presents tools that support developers in creating paper and computer-based prototypes which structure information in 3D space. The tools aim at creating depth layouts in an easy and quick way and at the same time encourage the developer to observe S3D design principles. These prototyping tools target the application of S3D to mobile applications, namely automotive and mobile phone UIs.

- **Chapter 6 – Paper Prototyping.** Paper prototyping is highly useful in early stages of the development process but is clearly limited when trying to arrange UI elements in 3D space. To overcome the flat nature of paper this chapter introduces the FrameBox and the MirrorBox, two novel tools for low-fidelity prototyping of S3D UIs. We present the design and development of the tools as well as their evaluation in two hands-on workshop sessions. In each workshop, experts in the fields of either automotive or mobile phone UIs compared both tools and traditional paper prototyping.
- **Chapter 7 – Computer-based Prototyping.** In this chapter, we present two tools that allow for prototyping digital 3D layouts. First, the S3D-UI Designer allows the design of virtual depth layers with a 2D UI and simultaneously depicts its 3D arrangement on a second 3D screen. We present the software design as well as an evaluation using the MirrorBox device as a 3D screen and a traditional desktop environment or an interactive tabletop for designing the depth layers. Second, the S3D-HUD Designer allows the prototyping of 3D HUDs. It provides a virtual 3D environment in which UI elements can be directly integrated. For the positioning and manipulation of UI elements the tool allows the use of keyboard and mouse as well as mid-air gestures.

Chapter 6

Paper Prototyping

Prototyping is an important step in the user-centered design process of GUIs to build usable systems. It allows for discovering usability problems, communicating ideas, and evaluating design options. There are several taxonomies describing the characteristics of prototypes. A classification into *throw-away*, *incremental*, and *evolutionary* prototypes highlights the way how the prototype or components of it are reused in the final product [51]. The prototypes' function set can comprise no functionality at all (*non-functional*) as well as a *fully functional* implementation. To save time and costs for the implementation either the number of the implemented functions is cut down (*vertical* prototype) or the level of functionality of all features is reduced such as they seem to work (*horizontal* prototype) [168]. The fidelity describes how much the prototype resembles the final design of the UI [43, 194]. This means that prototypes can be of *high-fidelity* and non-functional at the same time. For example, a Photoshop-generated design can completely provide the final look and feel of the product but does not comprise any functional elements. *Low-fidelity* prototypes allow a cheap, quick, and simple creation and can be easily modified as well [194, 245]. This enables the exploratory development of ideas and design alternatives which are particularly important in an early stage of the user-centered design process.

When it comes to developing a UI for 3D displays the appropriate use of depth as well as the exploration of the third dimension is challenging with conventional low-fidelity methods as paper prototyping. One approach to tackle this problem could be to initially develop the 2D layout and to consider the 3D effect in a later stage of the design process. However, we expect that this approach leads to a UI which applies 3D as a gimmick rather than effectively exploiting its potential by considering proper stereoscopic parameters. Looking at the game industry, Mahoney et al. [146] found that the S3D effect should be considered and involved from the beginning of the design process. We agree that it is necessary to deliberate the stereoscopic effect in a bottom-up rather than a top-down process.

To support the integration of S3D in early development stages, we present two prototyping tools, the FrameBox and the MirrorBox. The core idea is to augment paper prototyping in a way that maximizes the artistic freedom of the designer by exploiting all three dimensions easily and quickly. At the same time, the tools provide implicit guidance towards the effective use of 3D depth since it already implements some design principles we identified in Part III. Both tools target the prototyping for near view displays and do not take AR applications into account. In this chapter, we report on the development as well as the evaluation of the tools. In two workshops, experts in the fields of automotive and mobile phone UIs applied the FrameBox, the MirrorBox, as well as traditional paper prototyping to develop low-fidelity prototypes. The workshops show that the tools encourage the adherence to stereoscopic design principles, support collaboration, and foster creativity as well as the perceived fidelity.

This chapter is based on the following publication:

- N. Broy, S. Schneegass, F. Alt, and A. Schmidt. FrameBox and MirrorBox: Tools and Guidelines to Support Designers in Prototyping Interfaces for 3D Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’14, pages 2037–2046, New York, NY, USA, 2014. ACM

6.1 Related Work

Sketching on paper in the early stage of designing UIs is an important way to communicate and discuss ideas and requirements [10]. Snyder [221] defines paper prototyping as a method of brainstorming, designing, creating, testing, and communicating UIs. Due to the convenience of this approach, people at all stages of the development process and with diverse backgrounds can participate in the process, including designers, usability engineers, programmers, as well as end users. Walker et al. [245] showed that paper-based as well as computer-based prototypes are equally useful in finding usability issues.

Paper prototyping is well established for UIs targeting traditional input and output technologies. However, new technologies have arisen that impact the UI design and development. As a consequence, novel tools were developed that adapt paper prototyping to the respective requirements of the novel interaction technology. Wiethoff et al. [256] developed *Paperbox*, a toolkit that allows the exploration and creation of physical shapes for designing tangible interaction on interactive surfaces. Looking at AR applications, Lauber et al. [131] presented *PapAR* as a mean of designing UIs for a HMD used in the car. To address paper prototyping concepts for 3D displays, this chapter presents the FrameBox and MirrorBox as well as an evaluation of their applicability in the UI design process.

6.2 Designing the Tools

In the previous Part (cf., Part III), we established principles for designing and prototyping S3D UIs. With the tools presented in this section, we aim to provide means for designers to follow these design principles.

The third dimension makes it particularly challenging to use existing, state of the art, prototyping techniques for 2D UIs. As has been stressed earlier, paper prototyping has been shown to be highly useful in early stages of the development process [10] but is clearly limited when trying to arrange UI elements in 3D space. Hence, we built tools that can overcome the flat nature of paper for prototyping S3D UIs which allow information to be structured on different depth layers to build layered UIs. The core idea is to augment paper prototyping in a way that maximizes the artistic freedom of the designer while providing implicit guidance towards usable products. In the following, we derive requirements and determine physical dimensions for tools that can support low-fidelity prototyping in 3D space based on the design principles provided in Part III.

Viewing Distance and Depth Budget: First of all, designers need to identify the distance between the viewer and the screen on which the UI is being presented. Usually this distance is defined by the context in which the UI should be used. For example, in cars the usual distance between driver and the IC is 75 cm. The viewing distance then determines the depth budget in which UI elements can be positioned to provide a comfortable viewing experience. For example, Part III recommends parallax limits of 17.9 arc-min to the front of and 35.9 arc-min behind the screen plane for small viewing distances.

Target Interface Dimensions: The second requirement is the envisioned size of the target interface (width and height), e.g., of a public display, a mobile phone, or a automotive IC. Together with the viewing distance and depth budget the width, height, and depth of the available 3D space are defined.

Position of Depth Layers: The depth layer positions for structuring information in 3D space depend (a) on the distance of the viewer from the screen, which determines the available space (comfort zone) in z-direction and (b) of the minimum depth distance. For small viewing distances, a minimum distance of 2.7 arc-min between the depth layers is recommended (cf., Chapter 5).

Catering to these requirements allows us to build prototyping tools that support the user in creating UIs which minimize the visual discomfort S3D can potentially cause and allow different depth layers to be quickly and accurately distinguished. In this section, we describe two novel prototyping tools – the FrameBox and the MirrorBox. Both tools were designed to be used for arbitrary S3D UI design tasks and to map the specified requirements in the best possible manner.

6.2.1 FrameBox

The core idea behind the FrameBox is to allow the users to spatially position different UI elements which can be made from a variety of materials, including paper, transparency films, and 3D mockups created with a laser cutter or 3D printer. Hence, we designed a cubic box made of acrylic glass with a number of slots that represent the different depth layers. These slots allow for positioning UI elements on the z-axis in discrete steps. Within each slot, UI elements can be easily moved in the x-direction. Positioning on the y-axis can be achieved by means of paper-clips. Figure 6.1 depicts the FrameBox with several UI elements. In accordance with the specified requirements, we built a series of FrameBoxes for different application areas. One FrameBox is aimed for the design of automotive UIs and two for the design of mobile phones UIs (one for landscape and one for portrait mode). Figure 6.2 presents the three different layouts.

The automotive FrameBox is based on the dimensions of a conventional digital IC (i.e., screen size of 12.3”) and its typical viewing distance of 750 mm. The viewing distance allows for positioning UI elements 44 mm to the front of the screen and 107 mm behind the screen to maintain the comfort zone. This results in the following dimensions of the FrameBox for an IC application: 293 x 110 x 151 mm (width x height x depth).

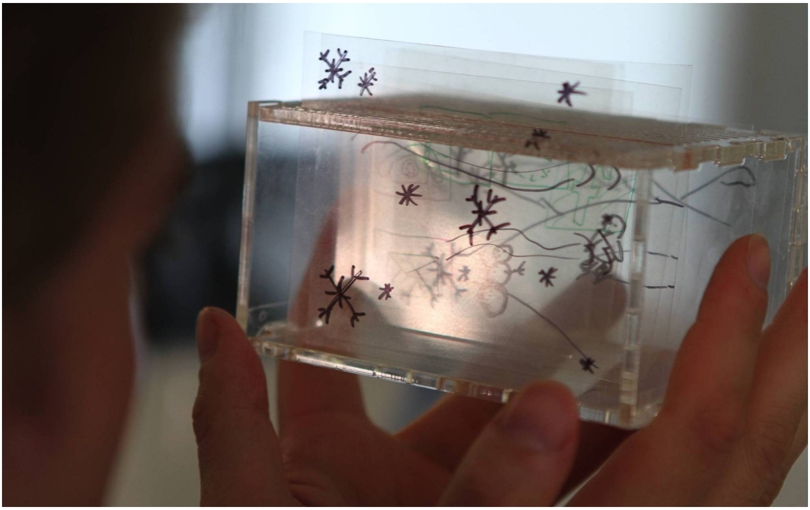

Figure 6.1: The FrameBox allows the user to sketch several depth layers in a quick and easy way.

For the mobile phone FrameBox we chose the size of the Samsung Galaxy S4 (i.e., screen size of 5") and a typical viewing distance of 350 mm. These values result in a comfort zone of up to 21 mm to the front and 50 mm to the back of the screen. Hence, the dimensions of the FrameBoxes are 111 x 62 x 71 mm.

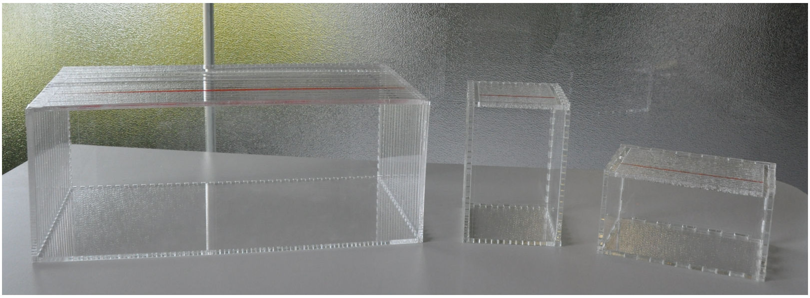

Figure 6.2: Frame Boxes for automotive and mobile phone applications (portrait and landscape).

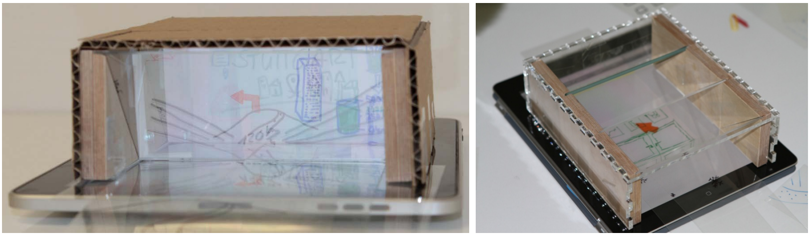

Figure 6.3: Our implementation of the MirrorBox provides three depth layers the users can sketch on transparency films. The left picture depicts the correct point of view showing the sketched layers. The right picture depicts the MirrorBox from the top with a cover made of transparent acrylic glass which facilitates the arrangement of the films.

All FrameBoxes were built using a laser cutter. The laser cutter templates are available for public use from our website[25]. As material we used transparent acrylic glass. We drew a red line along the slot referencing the screen layer which should make positioning in front of or behind the screen easy for the designers. The applied difference between the layers corresponds to an angular disparity of 3.6 arc-min. As a result, our implementations of the FrameBox offered 10 different depth positions behind and five in front of the screen.

6.2.2 MirrorBox

As a second prototyping tool, we designed the MirrorBox. The MirrorBox uses a number of semi-transparent mirrors in the front and a surface-coated mirror in the back. The mirrors are aligned in a way which allows the user to see the mirrored images of 2D elements projected from below. As a result, several depth layers are visible inside the MirrorBox. Figure 6.3 shows the MirrorBox from a front and top perspective. The mirrors are positioned one after another on top of a light source. Transparency films can be used to design UI elements, which are then sliced between the mirrors and the light source to make them visible to the user inside the MirrorBox. A cover of transparent acrylic glass allows the arrangement of the painted films without looking into the MirrorBox directly from the front.

We constructed a multi-purpose MirrorBox consisting of three mirrors with a size of 125 x 78 mm. Figure 6.4 depicts the construction data of the MirrorBox.

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[25] http://www.hcilab.org/p/3Dprototyping, last accessed October 11, 2015.

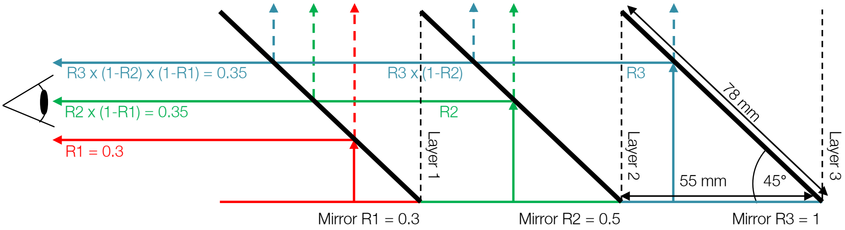

Figure 6.4: A side view of the MirrorBox clarifies its principle. The three mirrors have a different reflectivity (i.e., R1, R2, R3) to provide similar images for the viewer.

The mirrors are arranged behind each other and are horizontally tilted by 45 degrees. In this way, the mirrors generate three virtual layers by reflecting UI elements from below. We used a tablet as a light source. The mirrors have different reflectivity to provide the viewer with a similar brightness for all three virtual layers. The rear mirror reflects almost 100% (R3 = 1), the mirror in the middle has a reflectivity of 50% (R2 = 0.5), and the foremost mirror has 30% reflectivity (R1 = 0.3). This results in a total reflectivity between 30% and 35% for each virtual layer (cf., Figure 6.4). Since the mirrors are tilted by 45 degrees, the virtual images have a height of 55 mm. The distance between the layers is 55 mm. In consequence, the outer dimensions of our implementation of the MirrorBox are 125 x 55 x 165 mm.

6.3 Evaluation

To evaluate the potential of the presented tools, we exploratory examined them in two hands-on workshops with experts of two fields in HCI, namely, automotive and mobile phone UIs. We compared our approaches with paper prototyping, which is commonly used in early stages of the development process [10].

6.3.1 Study Design

We designed the workshops in accordance with a repeated measures design. The independent variable was the used prototyping technique (i.e., paper prototyping, FrameBox, MirrorBox). During the workshop, each participant worked with all prototyping techniques in three hands-on parts. Thereby, the participants used first paper prototyping before working with the MirrorBox and FrameBox. We counterbalanced the use of the two tools. After this hands-on phase, the participants filled in a questionnaire. The questionnaire assessed their design skills and asked them to rank the prototyping techniques from one (best) to three (worst) according to different items, to state their favored prototyping technique (multiple choices were possible), and to provide qualitative feedback. We used four items for the ranking addressing the expressiveness of the created prototypes, the usability of the tools, the effort in creating the prototypes, and the stimulation of creativity. Finally, we conducted a 30 minutes discussion phase in form of a focus group moderated by two researchers. During the discussion phase, participants were asked to comment on strengths and weaknesses of the techniques, particular questions that came up during the hands-on phase, and observations made by the researchers. We documented the workshop by videotaping the whole session and taking additional photographs.

6.3.2 Procedure

In the following, the general procedure is presented which we applied for both workshops. As participants arrived, we first gave them a brief introduction on S3D UI design. We particularly focused on explaining them design principles to use the 3D effect in a promising way (cf., Part III). The introduction took 10 minutes and slides were given to the participants as printouts for later reference. Then, the tasks for the hands-on phases were explained. We instructed the participants with a horizontal and a vertical prototyping task, depending on the workshop topic. Figure 7.1 outlines the procedure of the workshops.

In the hands-on phase, the participants were separated into two groups and were asked to work on the tasks by means of the three prototyping techniques. First, both teams used paper prototyping. As material we provided paper and post-its in different sizes and colors as well as colored pens. They were told that they had 15 minutes to work on the tasks and then had to present their ideas within no more than three minutes to the other group. After the presentation, one group was assigned the FrameBox and one group was assigned the MirrorBox and again given 15 minutes to work on the tasks. To each group, we also showed a brief concept video of the respective tool[26] which clarified its usage. We told them that they can reuse and integrate their ideas and the ones of the other group.

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[26] The concept videos are available from the ACM Digital Library and from http://www.hcilab.org/p/3Dprototyping, last accessed October 11, 2015.

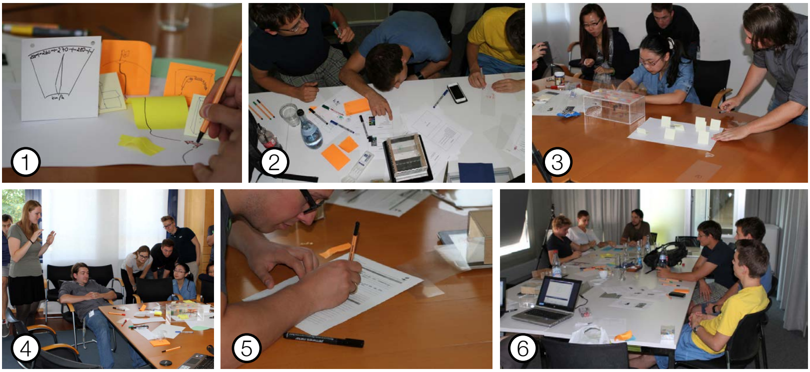

Figure 6.5: This image sequence documents the procedure of one workshop. After the two groups of participants received a brief introduction to S3D prototyping, they had to create a prototype out of paper, for example a 3D IC (1). After that groups used the MirrorBox (2) and the FrameBox (3) to refine their prototypes. The groups presented their results after working with each prototyping technique (4). In the end, the participants filled in a questionnaire (5) and engaged into a final discussion (6).

In addition to the paper prototyping material, we also provided them pieces of transparency films in different sizes and pens to write and draw on the films. After another three minute presentation, groups were asked to switch the depth layout tools and watch the respective concept video. After 15 minutes we concluded the hands-on phase with another brief presentation. In total, each group created three prototypes, one with each prototyping tool.

Following the hands-on phase, participants filled in the questionnaire and then entered the 30 minutes discussion phase. One workshop roughly lasted one hour and 45 minutes.

6.3.3 Workshop Topics and Participants

We conducted two workshops addressing two different application areas. In the first workshop, we focused on automotive UIs and addressed mobile phone UIs in the second workshop. The main reason for choosing these areas is that we assume 3D displays to be commonly used in these contexts in the near future. Each workshop followed the presented study design and procedure.

The automotive workshop ran with nine members of the HCI department of BMW, grouped into two teams of four and five participants, respectively. The participants (4 female, 5 male) were between 20 and 27 years old ($M = 24.2$, $SD = 1.9$) and their background ranged from design over engineering to computer science. All of them were phd, post-, or under-graduate students and were employed at BMW as interns or for accomplishing their theses at this time. They were experienced in creating 2D UIs but nobody had designed a UI for a 3D display before. We refer to these participants as P1–P9 in the results section. The horizontal prototyping task for this workshop was to design a 3D instrument cluster (IC) for a car. In addition, they were asked to integrate a conceptual navigation system within the IC that would provide guidance between two cities (vertical task).

Mobile phones are ubiquitously used and the number of apps available is constantly growing. Many apps are used on the go and, thus, an easy to understand UI is important. The mobile phone workshop ran with six under- and post-graduates with backgrounds in either computer science or design, grouped in two teams with three participants each. All of them were males, aged between 22 and 27 years ($M = 24.2$, $SD = 2.3$). All were experienced in developing applications for mobile devices. We refer to these participants as P10–P15 in the results section. The horizontal prototyping task of this session was to design the main screen of a mobile phone. For the vertical prototyping task, they had to design a weather widget that can be placed on the main screen.

6.3.4 Results

We collected results from the questionnaire and the discussion to get insights into how our concepts performed for creating low-fidelity 3D prototypes.

A ranking of the three prototyping techniques shows that most participants favored the FrameBox (n = 11), followed by the MirrorBox (n = 5) and paper prototyping (n = 5). Further findings are grouped around four dimensions that we consider to be particularly important for prototyping tools, namely, expressiveness, usability, effort, and creativity. Figure 6.6 shows the descriptive statistics of the ranking.

Expressiveness

Prototypes are often used to obtain early insights into concepts and, thus, the prototype needs to provide means for expressing and communicating the main idea. The questionnaire explicitly asked the participants to rank the prototyping techniques due to the expressiveness of the resulting prototypes. The ranking shows

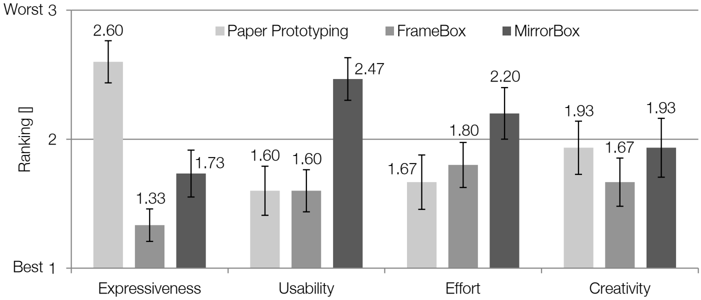

Figure 6.6: Means and standard errors for the rankings of the prototyping variants due to the dimensions expressivness, usability, effort, and creativity.

that participants attributed the highest expressiveness to the FrameBox ($Mdn = 1$), followed by the MirrorBox ($Mdn = 2$), and paper prototyping ($Mdn = 3$). We performed a Friedman ANOVA that shows statistically significant differences between the three tools, $\chi^2(2) = 14.000$, $p = .001$. As follow up tests, we used three Wilcoxon tests for pairwise comparison with Bonferroni corrections. The Wilcoxon tests show statistically significant differences for the FrameBox and paper prototyping, $Z = -3.226$, $p = .001$, as well as for the MirrorBox and paper prototyping, $Z = -2.586$, $p = .010$. The difference between the MirrorBox and the FrameBox is not statistically significant, $Z = -1.355$, $p = .175$.

The discussions reflect the findings of the questionnaire and provide further insights. Participants stated that “ideas are hard to communicate” (P4) using paper prototypes alone. Due to the two dimensional nature of paper the “3D space is difficult to imagine” (n = 3), “it is hard to visualize several depth layers” (P12), particularly if the user is “not able to draw 3D images" (P14). In conclusion solely using paper is “not sufficient for presenting the use of the z-axis” (n = 3). In contrast, the FrameBox as well as the MirrorBox represent the depth layers unambiguously and clarify depth positions. Participants feel the capabilities of the MirrorBox to be limited by just providing three layers, whereas “the FrameBox offers a greater scope” (P7).

Usability

Prototyping in user-centered design is often done with users that are not prototyping experts. Thus, it is important that the tools are easy to use. The questionnaire asked the participants to rank the tools due to their usability. They rated paper prototyping best ($Mdn = 1$) followed by the FrameBox ($Mdn = 2$) and the MirrorBox

($Mdn = 3$). We performed a Friedman ANOVA that shows statistically significant differences between the tools, $\chi^2(2) = 9.170$, $p = .010$. Using Bonferroni corrected Wilcoxon tests to follow up on this finding reveal statistically significant differences between the MirrorBox and FrameBox, $Z = -2.441$, $p = .015$, and between the MirrorBox and paper prototyping, $Z = -2.565$, $p = .010$.

Participants reasoned their preference for paper prototyping since it "is a well-known approach" (P10). Similarly, participants considered positioning elements on the layers to be very easy for the FrameBox (n = 4). Creating depth layers as well as modifying their x-, y-, and z-direction is perceived to be quick and simple. In contrast, positioning layers using the MirrorBox is considered to be tricky since overlapping snippets impede each other. In addition, some participants mentioned that it is confusing to correctly position the transparency films (mirror-inverted). Nevertheless, switching the depth position between the three layers for already arranged elements is perceived as fast and easy as this just requires to move the snippets along the tablet (P3, P12).

Effort

Prototyping aims at reducing time and costs by uncovering possible problems of the system under development as early as possible. It is particularly beneficial in an iterative design processes. Hence, refined versions are frequently tested. This suggests that the effort to create a prototype should be minimal. Therefore, participants ranked paper prototyping best ($Mdn = 1$), followed by the FrameBox ($Mdn = 2$) and the MirrorBox ($Mdn = 2$). The Friedman ANOVA shows no statistically significant differences, $\chi^2(2) = 2.393$, $p = .302$.

In the discussion, participants argued that paper prototyping is "good for first sketches and considerations" since it allows users to "generate and check out ideas quickly" (n = 3). Paper prototyping is considered to be effortless which "makes it easy to reject first sketches" (P10). The FrameBox supports the effortless design of realistic 3D impressions, whereas the MirrorBox is rated as more complex and sometimes even annoying, since the layers inside the small box are difficult to perceive without being positioned directly in front of it. Participants also felt that this makes collaboration among team members more difficult. This matches with our observations that the prototypes sparked quite a different amount of collaboration and discussion. With the MirrorBox, one member of the design team usually took the task to position elements while the others drew the elements. For the FrameBox, all participants designed elements and positioned them themselves.

Creativity

Prototyping sessions are often performed in stages where design decisions are not made yet. Thus, the tool should not hamper the creativity of the user. All three tools are ranked equally for supporting the user's creativity, ($Mdn = 2$). A Friedman ANOVA shows no statistically significant difference between the three techniques, $\chi^2(2) = 1.019$, $p = .601$.

The discussion showed that "paper prototyping fosters the flow of creativity due to starting from scratch on white paper" (P12) and "offers the highest degree of freedom" (P13). Prototyping with paper and using the FrameBox fosters communication and collaboration. Participants feel inspired by the visual effect from the backlight and the mirrored layers of the MirrorBox. However, four participants criticized that the mirror box restricts the 3D design space since it just offers the design of three depth layers.

6.4 Discussion

In the following, we discuss the presented results in regard to the observations we made during the workshops. We observed that the participants made use of the presented design principles to fulfill their tasks. While the MirrorBox restricts the depth layout to only three depth layers, the FrameBox provides participants much more artistic freedom. Nevertheless, the participants stick to the design principle of using no more than six depth layers while prototyping with the FrameBox (cf., Part III). Hence, this principle can easily be followed by the users even if the tool does not explicitly implement this rule. For paper prototyping, we noticed that the participants have difficulties in observing the comfort zone as well as the minimal recommended distance between depth layers. Consequently, it is beneficial to integrate these guidelines in the tool in a way such that the designers can take the available depth relations into account. Furthermore, the participants propose an iterative process which involves a first concept draft based on paper prototyping and a later refinement using the FrameBox.

The conducted workshops show that our tools complement the strengths of paper prototyping – particularly low effort and support for creativity – with high usability and means for expressiveness. The participants tried to cope with the fact that paper prototyping makes it difficult to position elements in 3D space. This comes at the cost of increased effort. For example, participants spent a considerable amount of time during the paper prototyping session making post-its 'stand' behind each other to reflect several layers or trying to build 3D objects out of paper. In contrast, the positioning of elements in 3D space is supported by the MirrorBox and the FrameBox. The use of our tools allowed the participants to concentrate on ideas, exploring the positioning of objects, and object size. The participants liked to use paper prototyping in combination with the FrameBox as it has a low barrier for participation in the prototyping process but supports the spatial arrangement and the integration of 3D objects, as well. In contrast, the MirrorBox narrows the depth layout to three layers and does not allow the integration of 3D objects.

Furthermore, we have seen in the workshops that the prototyping tools help to effectively communicate design decisions within the team and to outside observers. The participants reported that it is easier to understand the idea of the other group as they presented their results with the MirrorBox or the FrameBox in contrast to seeing the results just as a paper prototype. This finding is supported by the results of the questionnaires regarding the expressiveness ratings. A low barrier for participation and the expressiveness is especially important for the UI development process as it often involves developers with different backgrounds.

Participants also expressed a clear interest in increasing the fidelity of the MirrorBox. While in our case, the iPad is only used as backlight, they suggested using an external screen or tabletop surface that would allow users to sketch UI elements and display them immediately on the tablet. Since the usability of the MirrorBox is decreased due to the complex positioning of the transparency films, we recommend to use the MirrorBox for reflecting digital depth layers rather than painted films or for even mixing both modalities.

Finally, we see potential in augmenting the FrameBox with 3D elements, for example, from a 3D printer. In the automotive workshop we observed participants exploiting ways of modeling 3D objects. One group used the upper back part of the sticky notes to attach interface elements to paper. Another group used transparent scotch tape to create objects like mountains or buildings for the navigation system and integrated those 3D elements in the FrameBox.

6.5 Summary

In this chapter, we presented the MirrorBox and the FrameBox, two display layout tools for prototyping stereoscopic UIs. We designed the tools in a way that supports the simple and quick creation of low-cost 3D prototypes. Since we already incorporated S3D design principles within the tools, they support designers to follow these principles. Beside informing about the general design of the tools and their requirements, we demonstrated the approach by means of applications for a mobile phone and an automotive IC. Based on these two cases, we provide detailed information on how to adopt our idea to arbitrary application areas. We evaluated the tools by conducting two workshops with students experienced in usability engineering. In our evaluation, we show that our prototyping tools extend paper prototyping when it comes to designing UIs for 3D displays. They encourage the adherence to stereoscopic design principles, foster creativity in 3D space, and increase the expressiveness of the created prototypes. In general, we see great potential in using the FrameBox in combination with paper prototyping in an early stage of the development process. In addition, the MirrorBox is suitable for creating prototypes of higher fidelity by representing digital content instead of sketched layers. We address this aspect of the MirrorBox in the following chapter.

Chapter 7

Computer-based Prototyping

In the previous chapter, we introduced two physical tools that allow prototyping S3D interfaces by sketching different depth layers. The next step in the user-centered design process foresees the refinement of the ideas and concepts generated by paper-based prototyping techniques. At this point, the increase of the fidelity requires the integration of digital content. Tools such as Balsamiq [63] and Axure [210] enable the user to create high-fidelity but non-functional prototypes. In this way, the look and feel of the UI can be designed in detail without any programming experience. In general, digital prototypes are commonly incremental and iterative prototypes as they are easy to duplicate, distribute, and refine. The computer-based creation of prototypes has the advantage to directly generate XML or HTML code that can be reused in the final product.

In this chapter, we present tools that address the prototyping of digital stereoscopic UIs while maintaining the ease of use of interaction techniques that are commonly applied for 2D GUIs (e.g., mouse and keyboard input). We present two tools, the S3D-UI Designer and the S3D-HUD Designer. The S3D-UI Designer allows prototyping for different 3D output devices. The core idea of the S3D-UI Designer is to design several depth layers using a 2D interface, while the 3D output is simultaneously visualized by a 3D display. Hence, the S3D-UI Designer requires two displays. A first implementation of the S3D-UI Designer applies the MirrorBox as output device and a desktop environment with keyboard and mouse or an interactive tabletop for designing the depth layers. We evaluate this implementation of the S3D-UI Designer for developing a 3D mobile phone application in workshops with 26 students. As a second tool we present the S3D-

HUD Designer that specifically addresses the prototyping of automotive HUDs. The tool allows to augment a stereoscopic still image, for example depicting a traffic scenery, with stereoscopic content elements. In contrast to the S3D-UI Designer, the S3D-HUD Designer requires just one display. Hence, the design of the prototype as well as the 3D output takes place on one 3D display. The user can interact with the S3D-HUD Designer using keyboard and mouse as well as mid-air gestures. In a user study with 30 participants we compared the mouse with the gesture interaction. In the following, we report on the iterative development, design, and evaluation of the S3D-UI and S3D-HUD Designer.

This chapter is based on the following publication:

- N. Broy, M. Nefzger, F. Alt, M. Hassib, and A. Schmidt. 3D-HUDD – Developing a Prototyping Tool for 3D Head-Up Displays. In *Human-Computer Interaction – INTERACT 2015*, volume 9299 of *Lecture Notes in Computer Science*, pages 300–318. Springer International Publishing, 2015

7.1 Related Work

Prototyping GUIs is important in the design process of building usable systems. It is applicable at different stages, ranging from early sketching on paper to an almost implemented product [194]. When sketching on paper, prototyping can even be done without any programming knowledge. It is used during brainstorming sessions or for designing, creating, and testing UIs [221] and offers a way of rapidly presenting and communicating ideas [10]. At the same time, people not used to sketching may be afraid of drawing ugly interfaces and, hence, be reluctant to express themselves [10]. In addition, Sefelin et al. [211] show that test participants prefer digital prototypes over paper prototyping for early evaluations. Walker et al. [245] found that the participants commented more frequently on computer than paper prototypes while the paper as well as the digital prototypes identified the same number of usability issues.

However, creating digital prototypes typically requires programming skills and technological expertise when novel input or output technologies are intended. Possible solutions are tools that allow digital prototypes to be rapidly created without the need of expert knowledge. Such tools have been developed for a variety of application areas. Weigel et al. [249] developed a tool which allows creating prototypes for mobile projection applications. Moreover, there are tools that enable the creation of context aware applications. For example, *iCAP* [222] is a tool for prototyping context-aware applications based on if-then rules without writing any code. *Topiary* [139] allows for designing applications taking the location of people or places into account. Additionally, there are tools which address the use of hardware elements. The *CalderToolkit* developed by Lee et al. [133] is a hardware toolkit to rapidly prototype functional interactive devices for tangible UIs. In regard to the automotive context, Schneegass et al. [209] presented *MI-AUI* that allows the simple creation of in-car UIs using tangible controls. Moreover, prototyping tools also integrate several fidelity levels in one interface [43]. De Sá [48] developed a prototyping tool for mobile devices which supports the creation of prototypes ranging from sketch-based to functional interactive software prototypes.

There are several commercial tools, such as Balsamiq [63] and Axure [210] which support the creation of detailed UI prototypes for websites and mobile applications. In addition, a lot of developers use tools such as Microsoft PowerPoint[27] and Adobe Photoshop[28] to create simple wireframes but also sophisticated UI designs [161]. Presente3D[29] is an extension for PowerPoint that enables the creation of stereoscopic presentation slides. However, to our knowledge there is no tool that supports prototyping S3D UIs per se.

7.2 Prototyping Layered User Interfaces

Creating 3D UIs is nowadays possible, using authoring tools such as Unity, Maya, Blender, or 3D Studio Max. While they offer powerful means of creating, positioning, and animating 3D objects, such tools raise a number of challenges. First, they were not designed to create UIs, particularly stereoscopic UIs. As a result, they do not offer any support for creating a sophisticated S3D UI, for example, through notifying the designer of breaking S3D design principles such as too large depth budgets or elements positioned too close to each other in order to distinguish their depth (cf., Part III). Second, such tools require trainings and expert knowledge. Hence, they do not support the rapid prototyping of S3D UIs as is often required in early phases of the design process.

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[27] https://products.office.com/en-US/powerpoint?omkt=en-US, last accessed October 12, 2015.

[28] http://www.adobe.com/products/photoshop.html, last accessed October 12, 2015.

[29] http://www.presente3d.com/, last accessed October 12, 2015.

We tackle these challenges by developing the S3D-UI Designer, a tool which guides the designer towards prototyping powerful and usable S3D interfaces. As we envision to use the S3D effect for structuring the UI, we draw upon the concept of layered UIs [85]. Prior work has shown that structuring information on layers can significantly improve search times [102]. Additionally, the use of layers is also interesting from a designer perspective as this metaphor is applied by typical graphic editors (e.g., Photoshop). Thus, the designer can create the layers one-by-one. However, it is difficult to understand how depth layers interact with each other (i.e., obstructions, interplay of colors, etc.). Including 3D elements further increases the complexity of the UI. For this reason, we do not consider those elements and initially focus on prototyping several depth layers.

In the following, we present the S3D-UI Designer which allows prototyping low- as well as high-fidelity layered UIs while the designer can instantly observe the final output on a 3D display. Our implementation of the S3D-UI Designer applies the MirrorBox which we already explored as a tool for paper prototyping (cf., Chapter 6). Note, that the software is not limited to the MirrorBox but can be extended to any 3D output (e.g., for an autostereoscopic display) due to its modular implementation. We chose the MirrorBox as a starting point since the participants of the workshops presented in Chapter 6 showed a clear interest of using the MirrorBox for generating digital prototypes. In this section, we present the general concept of the S3D-UI Designer and report on two expert workshops, where designers had to create layered 3D UIs with common design tools. Based on the outcomes of the workshops, we conceptualize the S3D-UI Designer and present its implementation. We evaluate the tool with 26 participants and show that it strongly supports designers in creating prototypes of layered 3D UIs.

7.2.1 Exploring Digital Prototyping for 3D Displays

As shown in related work, few solutions exist that optimally support prototyping for 3D displays. We focus on layered UIs as one particular use case. In this way, we can apply well-known 2D interaction techniques and avoid the complexity of 3D interaction. We envision our research to provide fundamental knowledge upon which also non-layered S3D UIs can draw in the future. The basic idea of the S3D-UI Designer is a 2D UI that allows the design of several depth layers and the instant display of the depth layout on a 3D output device. This interface provides input controls as well as a 2D display, which is referred to the input display in the remainder of this chapter. The 3D display is referred as output display and represents the stereoscopic prototype. While in theory the number of

Figure 7.1: We ran two expert workshops to identify requirements of a tool for prototyping digital 3D layouts.

possible layers is only limited by the employed display technology – solutions range from autostereoscopic displays [54] to several layers of transparent screens (i.e., MLD) [8] – Chapter 5.2 recommends a maximum of 6 layers when it comes to structuring information on different layers. We chose a technology supporting a limited number of layers only. To bridge the gap from paper to digital prototypes we implemented a first version of the S3D-UI Designer with the MirrorBox (cf., Chapter 6) as a 3D display. We positioned the MirrorBox on the display of a tabletop to reflect three virtual layers (cf., Figure 7.1). We deliberately opted for this setup for several reasons. Beside offering a seamless process from paper-based to computer-based prototyping and even mixing both mediums, we reduce the complexity of layered UIs by limiting it to three static depth layers. Nevertheless, we envision a dynamic layout of several layers as a further refinement of the tool for future work. Moreover, the MirrorBox neither requires glasses nor has technical shortcomings as autostereoscopic technologies (e.g., crosstalk, maintaining a defined sweet spot). It clearly differentiates the layers and, thus, eases up the understanding of layered 3D UIs and lowers the level of entry for designing such systems.

Expert Workshops

To explore core requirements for a 3D prototyping tool, we ran two expert workshops. The objective of the workshops is to identify important features and functions that would best support designers during their work. In these workshops, participants solved different design tasks using two 2D tools. We used the MirrorBox as 3D output device. For creating the UI, we attached an external monitor with keyboard and mouse. Figure 7.1 depicts this setup.

We selected Microsoft PowerPoint and Adobe Photoshop for creating the UIs because these tools are commonly known by potential users. Whereas Powerpoint allows for quickly arranging items and using pre-defined elements, Photoshop provides a higher degree of artistic freedom when it comes to creating custom elements. In both programs we provided a template consisting of three distinct areas placed on top of each other. However, both tools required further interaction steps to display the content with the MirrorBox. The Photoshop version required to save the file, while the Powerpoint solution needed to mirror the layers and aligning the mirrored presentation according to the MirrorBox.

The expert workshop was framed around creating a layered UI for a multilayer mobile phone. The participants had to solve two tasks. The *menu task* was about the design of an hierarchical menu consisting of different applications (e.g., phone book, music, email). In the *email app task*, they should create a layered UI for an email application. In addition, we let the participants design the UI with two objectives. In the *free design task*, we provided the task in text form, leaving participants the freedom to come up with an own solution. In the *mockup task*, participants were presented a 2D mockup which they rebuilt for a 3D UI.

Workshop Procedure

We conducted two workshops, one with three and one with four participants. The first workshop group started with freely designing the menu (Powerpoint) before designing the email client based on the provided mockup (Photoshop). The second group was asked to first design the email client (Photoshop) before continuing with refining the mockup menu (Powerpoint).

Upon arriving at the lab, participants filled in a demographic questionnaire and received a short introduction to the main principles of 3D UI design (cf., Part III). Then, we explained the setup and how to use the prototyping tools. After that, they started with the *free design task*. After 20 minutes they briefly presented their results before continuing with the *mockup task*. For this task, they used the program they did not work with in the first task and had a time frame of 10 minutes. Again they gave a short presentation of their results. The workshop concluded with a 30-minute *discussion* phase, which allowed participants to come up with further ideas for the prototyping tool and discuss them with the group.

Findings

We recruited 7 participants (4 female, 3 male), aged between 20 and 29 years ($M = 23.3$, $SD = 2.8$), with backgrounds in design and computer science. Participants were undergraduates and postgraduates. Observations from the workshop and qualitative feedback from the subsequent discussions lead to four major findings.

- **Maintain opportunity to collaboratively prototype the UI.** The participants liked to collaboratively work on the UI and instantly discussed the results, rather than designing elements separately. Our setup allowed only one person to create and arrange elements at a time while the others observed, commented, and provided suggestions. Being asked later whether this was an issue and whether it would have been better to, for example, provide every participant a device to work in parallel, all participants agreed that this would have destroyed the collaboration resulting in weaker outcomes.

- **Realtime feedback of spatial arrangement.** The participants criticized the interaction steps that were necessary to view the 3D result inside the MirrorBox. In consequence, the instant synchronization of the input and output display is essential. A further weakness identified by the participants was that the used tools did not provide any feedback on whether their choice of arranging UI elements would lead to a satisfactory result. In many cases, participants found that placing elements resulted in overlaps with objects already placed on other layers. In these cases, they needed to rework the interface. Hence, they requested features such as reference lines to align content across layers and automated feedback on overlapping objects.

- **Enabling several viewing options for layers.** The participants envisioned to switch the arrangement of the layers visualized by the input display. In our setup the layers were stacked on top of each other. Beside displaying the layers individually and changing their order, the tool should provide a combined view. Rather than rendering each layer on separate display spaces the combined view renders all layers on one display space to facilitate the transition for the users between the input display and the 3D output display.

- **Focus on depth layout features.** Participants where sometimes overwhelmed and frustrated by the number of features and controls especially provided by Photoshop. This suggests to offer the most important design functions instead of including complex drawing and shader methods. As a conclusion, the tool should focus on arranging GUI items on the layers while their detailed design can be achieved with other programs such as Photoshop.

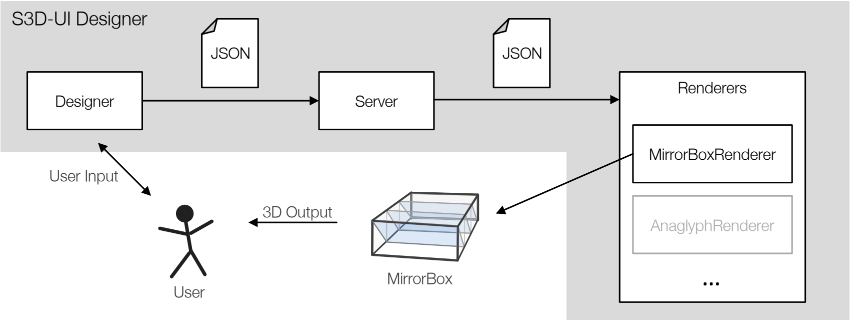

Figure 7.2: The S3D-UI Designer is based on a client-server architecture.

7.2.2 The S3D-UI Designer

The findings from the expert workshops served as a basis to inform the design of the prototyping tool. We implemented the tool as a client-server based web application for use on different input devices, such as desktop environments, tablets, or tabletops. Data is stored on a server to be accessible everywhere. We also implemented an XML-based data format to exchange the generated 3D layouts and to extend the tool for other output devices.

Implementation

The S3D-UI Designer consists of a client-server architecture and implements one server and several clients (cf., Figure 7.2). One client represents the *Designer* and the other clients are the *Renderers* enabling the output for different 3D display devices. As a first step, we implemented the *MirrorBoxRenderer*. The *Designer* implements the 2D GUI that allows for designing several depth layers.

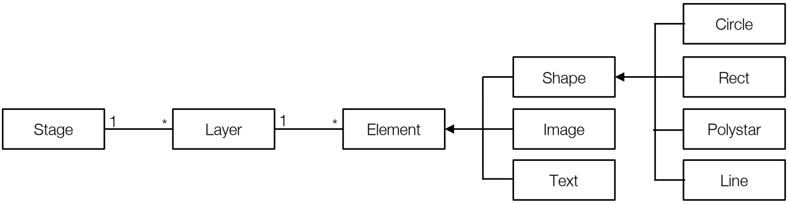

Figure 7.3: The data model represents a layered UI.

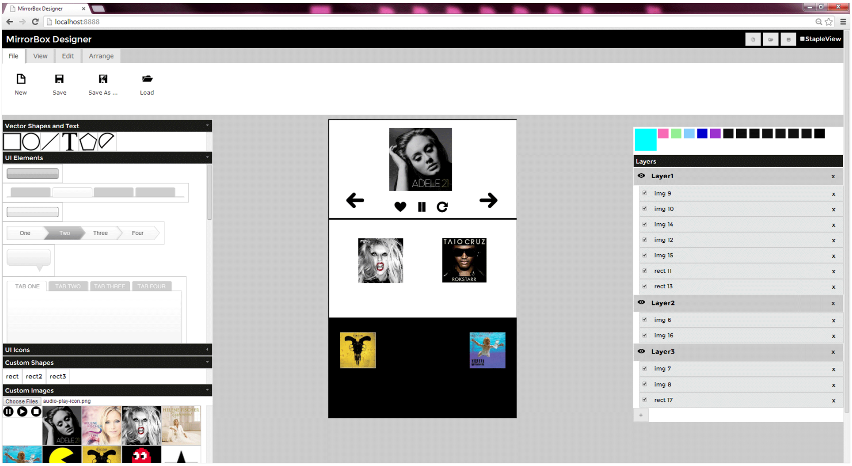

Figure 7.4: The S3D-UI Designer allows to create the visual layout of the three virtual layers and provides different 2D views on these layers.

The depth layers that are created using the *Designer* are parsed into a JSON model representing the layered UI. The data model is outlined in Figure 7.3. The so-called stage can contain multiple layers. Each layer consists of multiple children. Those children can be vector shapes, images, and text. The JSON format allows the data exchange between clients and server, the permanent storage of created UIs, and the development of different *Renderers* in the future (e.g., for an anaglyph stereoscopic output). We implemented the data model in JavaScript to display it in the *Designer* and the *MirrorBoxRenderer*.

Since our setting just needs a one-way communication, the *Designer* sends the JSON file to the server which pushes the data to all *Renderers* via UDP. The server is based on *Node.js*. To enable the Node server to send the data to the *MirrorBoxRenderer* we use socket.io. The *Renderers* parses the received data and renders the layers in accordance with the 3D ouptut device. In our case, the *MirrorBoxRenderer* scales and arranges the three layers by means of the layout of the MirrorBox.

Graphical User Interface

The *Designer* (cf., Figure 7.4) consists of four areas. On top, a tab sheet allows to toggle between four tabs (i.e., file, edit, view, and arrange). The file tab provide means to load and save files. From the content area placed on the left side, UI elements can be chosen. In particular, we offer, vector-shapes (UI elements, icons), images, and text. Images can also be loaded from the local file system which allows the integration of elements that were created with other tools. The edit tab allows the user to modify the properties (e.g., position, scale, rotation, color) of the UI elements. In the center, the depth layers are depicted. Note, that in theory an unlimited number of layers could be created. Based on the findings from the workshop, we provide means to switch between two views with the view tab: one shows the layers stacked on top of each other and one depicts a combined view. In addition, the tool checks for overlapping UI elements and highlights colliding items. The user can add horizontal and vertical reference lines that are displayed across all layers. Finally, the right area shows the different layers and their elements. Using the arrange tap, elements can be grouped and ungrouped. The entire UI is drag and drop enabled, hence allowing for an easy placement and arrangement of the different elements.

7.2.3 Evaluation

In order to explore the usability of the tool, we conducted a user study. In particular, we were interested how the tool as well as the working environment support collaboration in exploring UI ideas. Hence, the participants designed the layers on a touch surface of a Microsoft PixelSense as well as using a classical desktop setting with a desktop monitor, a keyboard, and a mouse. The study was designed as a repeated measures experiment with the working environment as independent variable (touch vs. desktop).

Setup and Procedure

As in the previous workshops, participants received two tasks. The tasks were formulated in an open manner, leaving the participants more room to explore the possibilities of the tool. In both setups, participants designed prototypes for a multilayer mobile phone. In the *application task* participants created the UI for a music application. In the *game task* their assignment was to adapt the popular arcade game *PacMan* to 3D.

The participants were separated into groups of three participants for each session. As in the previously described workshops, the study started with a short introduction about S3D and we briefly explained the tool's main functions. Then we presented the tasks and the working environments. For each task, the participants had 25 minutes to design the required UI. Thereby the participants used the

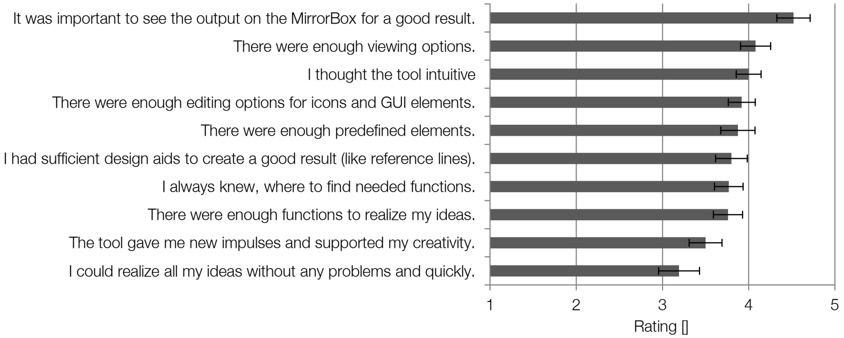

Figure 7.5: Means and standard errors of the ratings for the final questionnaire's items rated on five-point Likert scales (1=strongly disagree to 5=strongly agree).

desktop setting for one task and the touch surface for the other task. After each task, the participants rated statements about collaboration, creativity, and usability on five-point Likert scales. To minimize sequence effects, we counterbalanced the order of the conditions - touch or desktop - across groups. After the hands-on phase, the participants filled in a final questionnaire. They rated statements about the system's functionality and its usability on five-point Likert scales (cf., Figure 7.5). The study concluded with a 15 minute discussion about the tool and its usage in the two working environments. One workshop lasted about 90 minutes.

Findings

We recruited 26 people (14 female, 12 male, P1–P26), aged between 22 and 56 years ($M = 26.1$, $SD = 6.5$), with backgrounds ranging from sociology over management to computer science.

The final questionnaire (cf., Figure 7.5) and the discussion show that the participants were overall satisfied with the usability and the functionality of the tool. One experienced designer said: "With the easy usage of the S3D-UI Designer, people with no experience have the possibility to quickly try out design ideas. [...] This makes designing accessible for everyone." (P16). This was validated by an inexperienced participant from another group. He admitted "I cannot do anything in Photoshop. Here I understood everything immediately" (P10). Participants stated they like the minimalist, clear design of the tool and the simplicity of its UI, which contributed to its intuitiveness. In general, the final questionnaire (cf., Figure 7.5) and the discussion reveal that the major benefit of the tool is

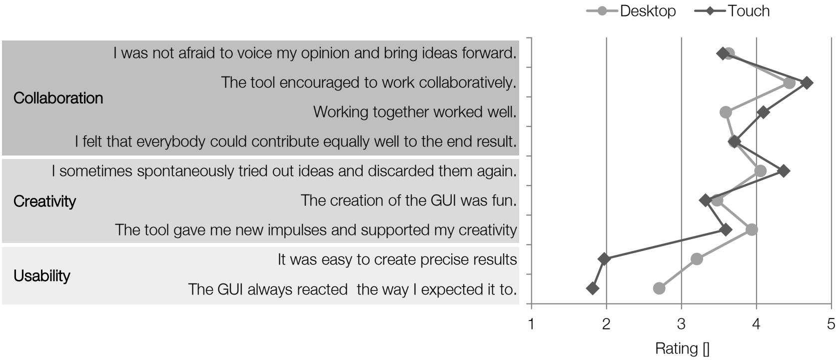

Figure 7.6: Mean values of the ratings for using the touch interface and the desktop setting. The items are rated on five-point Likert scales (1=strongly disagree to 5=strongly agree).

the interplay of the MirrorBox and the S3D-UI Designer since it supported the "finding of a feeling for 3D" and "created a relaxed atmosphere". One participant outlined this advantage: "It was very cool to see the output on the MirrorBox, as it differs completely from the result on the display." (P5). Nevertheless, the arrangement of the input devices as well as the 3D output device is crucial as one participant noted the effort it took to look into the MirrorBox was "inconvenient" (P4). It should be positioned prominently near the eye level.

Figure 7.6 presents the means of the ratings for the statements concerning collaboration, creativity, and usability. We aggregated the data by these dimensions. The aggregated data shows that touch ($M = 4.106$, $SD = .807$) outperforms the desktop setting ($M = 3.942$, $SD = .782$) for collaboration. A t-test reveals that the difference is not statistically significant, $T(25) = 1.842$, $p = .077$. While the rating of creativity is rather similar for touch ($M = 3.858$, $SD = .849$) and the desktop environment ($M = 3.923$, $SD = .656$), $T(25) = -.502$, $p = .620$, the usability is rated significantly higher for the desktop setting ($M = 3.058$, $SD = .942$) than for the PixelSense ($M = 2.000$, $SD = .980$), $T(25) = -5.543$, $p < .001$. In the discussion, participants had different arguments to the advantage of touch as well as the desktop environment. In accordance with the usability ratings, benefits of the desktop setting comprise a higher degree of precision and ease of control ("the desktop is the better choice if precise results are needed"). The most recurring argument in favor of touch was the support of collaboration. This finding corresponds to our observations during the study and the trend of the ratings. We noticed that for the desktop setting, usually one person operated the program, while the other team members commented, gave instructions, or voiced ideas. At the interactive table everyone was actively engaged. Some participants stated that touch was more fun ("fun to simply drag the elements into the canvas") and enhanced creativity ("the level of interaction is much higher so that a lot more ideas come to mind").

7.2.4 Discussion

The S3D-UI Designer is a tool that enables the prototyping of digital stereoscopic UIs. In a first step, we implemented the tool for designing three virtual depth layers that are instantly displayed on the MirrorBox. We used the MirrorBox as it allows the seamless transition from paper to computer-based prototypes. Due to the modular implementation of the tool it can be extended to several 3D output formats and displays. For future work, the S3D-UI Designer needs to visualize the correct use of depth layers when it comes to the design of more than three layers and their flexible positioning along the z-xis.

The iterative process in developing the S3D-UI Designer provided requirements for tools that support the prototyping for 3D displays. First, the instant stereoscopic visualization is crucial for the effective development of S3D UIs and the exploration of S3D layouts. Second, the prototyping tool does not need to incorporate comprehensive design functions as for example Photoshop. Instead, it should focus on creating 3D layouts. Third, a flexible visualization of depth layers as well as design aids across layers such as reference lines and highlighting of occlusions are important features for prototyping layerd UIs. Fourth, the working environment has a potential influence on the prototyping process and its outcome. While a traditional desktop environment maximizes usability and offers the generation of prototypes with an increased fidelity, an interactive touch surface fosters collaboration for exploring design ideas and variants. Nevertheless, future work has to explore how the collaboration can be maximized through the tool and its interaction design. For example, the integration of hand held devices for each designer could support collaboration and the discussion of individual ideas. Moreover, the extension of the tool to further display devices can unfold further requirements.

7.3 Prototyping 3D Head-Up Displays

In the previous section, we presented the development of a tool that allows the prototyping of GUIs for 3D displays. This tool focuses on structuring information on depth layers rather than targeting mixed or augmented reality applications. When it comes to prototyping UIs for such applications further requirements arise. Hence, the 3D layout of the virtual content depends on the properties of the augmented (real) world scenery. State-of-the-art prototyping or mockup tools, such as Balsamiq [63] or Axure [210], are unsuitable for two reasons. First, they neither allow UI elements to be positioned in 3D space nor do they support the registration of these UI elements with objects in the environment. Second, with the aforementioned tools it is in general not possible to render the UI and environment stereoscopically, making it difficult to understand the depth layout and thus identifying strengths and weaknesses of the design.

In this section, we address the aforementioned challenges by developing a tool for prototyping UIs for stereoscopic HUDs. We present the development, implementation, and evaluation of the S3D-HUD Designer. The tool should allow the user to rapidly create 3D HUD concept layouts in order to gain early insights through qualitative and quantitative evaluation. In contrast to the S3D-UI Designer, the S3D-HUD Designer embeds the controls of the prototyping tool into the 3D output to facilitate the creation of mixed and AR applications. In consequence, the tool depicts the environment, the prototyped interface, as well as the prototyping controls in one 3D display. Therefore, the tool needs to provide means to easily position and manipulate objects in 3D space. Since 2D devices, such as keyboard and mouse, lack intuitiveness when it comes to manipulating 3D objects [125], we opted to integrate a technology that enables mid-air gestures to better support the user creating the prototype. The work of van Beurden [239] demonstrates the potential of gesture interaction in 3D virtual environments in terms of hedonic quality. However, his studies show that traditional input devices outperform gestures in regard to pragmatic quality.

For the development of the S3D-HUD Designer, we used a similar approach as for the S3D-UI Designer. An initial expert workshop provides requirements on which the tool is based. We implemented the tool in a way that the user can interact with mouse and keyboard but also using gestures. A final evaluation of the tool proves that the use of mouse and keyboard generally outperforms gesture interaction. Nevertheless, in some cases gestures provide more precise results.

Table 7.1: Results from the first part of the workshop. Participants came up with a list of features and prioritized them.

Features	**Priority**
Altering position, orientation, and scale in 3D space	high
Positioning the layer with zero parallax	high
Import graphics and objects	high
Insert text	high
Save and load prototypes	high
Drag & Drop	medium
Change the 3D scene in the background	medium
Visualization of depth positions	low
Change color settings	low
Change font	low
Preset of 3D objects	low
Preset of HUD graphics	low

7.3.1 Informing the Design

The objective of this work is to support the development of the depth layout of a stereoscopic HUD. The strong advantage of a 3D HUD is embedding the displayed content into the real world based on all three dimensions. There are several options to simulate or to implement a stereoscopic HUD. Low-fidelity variants of a stereoscopic HUD can use S3D images or videos of a driving scene to illustrate the spatial concept of the UI in regard to the real world. The integration in a 3D driving simulator or the use of see-through 3D displays such as a binocular see-through HMD in a real world environment can strongly increase the fidelity. Since we aim at earlier development stages which involve the rapid creation of concept layouts and their initial evaluation, our goal is to provide a tool which allows for quickly developing low-fidelity stereoscopic HUD prototypes. To understand the requirements and inform the design of such a tool, we conducted an expert workshop at the outset of our research, focusing on two objectives: (1) Identifying and prioritizing functions of a prototyping tool for a 3D HUD and (2) collecting ideas for a suitable interaction concept in 3D space.

Procedure

For the expert workshop we recruited seven participants (i.e., phd, undergraduate, and postgraduate students) with backgrounds in design, psychology, or computer science and invited them to a workshop at BMW Research and Technology. All participants were employed at BMW as interns or for accomplishing their theses

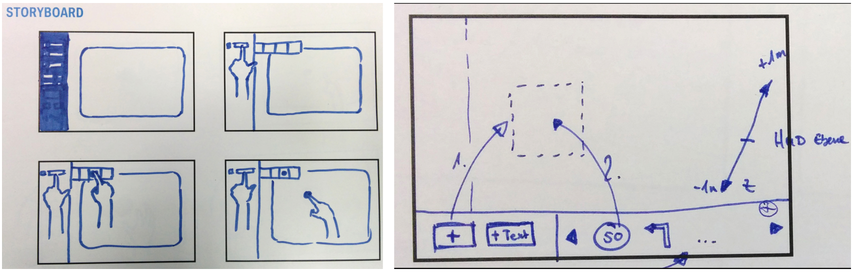

Figure 7.7: The left images illustrates the storyboard of group A. The right image presents the interface sketched by group B.

in the field of automotive UIs. We started the workshop with a short introduction on 3D HUDs by showing participants a stereoscopic picture of a 3D HUD in front of a 3D street photography on a shutter notebook. We briefly discussed several use cases for such displays. After that, we explained to the participants our motivation and ideas behind creating a stereoscopic HUD prototyping tool. The rest of the workshop was split into two parts.

In the first part, participants had to come up with features a 3D prototyping tool should include and wrote them down on post-it notes. After the brainstorming, ideas were presented by participants to the plenum who discussed, grouped, and prioritized the ideas. In the second part, the participants were divided in two groups. The task for each group was to sketch the interface of the prototyping tool and to think about how they would interact with the interface. Participants were encouraged to consider reasonable gestural interactions as input modality.

Results

Results from the first part of the workshop are depicted in Table 7.1. Participants felt suitable means for positioning objects to be of utmost importance. In addition, the import of graphics and objects was considered to be important. Presets for 3D objects and graphics were considered less important. Regarding part two, the groups came up with fundamentally different concepts (cf., Figure 7.7). While group A designed the interaction using gestures as single interaction modality, group B suggested mid-air gestures to be used optionally.

Group A focused on the storyboard and the gesture input. Using the left hand for pointing gestures selects a function of a menu, for example, adding an element from an available object list to the 3D scene. The right hand is responsible for object manipulation, for example, positioning and scaling.

Group B focused on sketching the UI. The interface consists of a panel in the left and lower part of the display. The panel in the lower part allows different elements to be added to the scenery displayed in the remaining display space. The group suggested that graphics should be designed in an external program, such as Adobe Photoshop, and subsequently imported into the tool. The panel to the left offers functions for manipulating the objects in the scenery as well as for clustering and registering them with different depth layers. Interaction is based on mouse and keyboard. Gesture input can be optionally included for object manipulation. As an important feature, group B presented a visualization of the z-axis representing the depth positions of the objects.

7.3.2 The S3D-HUD Designer

Based on findings from the expert workshop, we implemented the S3D-HUD Designer. In the following, we describe the design of the UI, the depth management, the interaction with the interface, as well as its implementation.

Graphical User Interface

Employing the What-You-See-Is-What-You-Get paradigm, we designed the GUI of the tool to allow users to immediately perceive the look-and-feel of the UI. Following recommendations from Schild et al. [205], all UI elements are positioned on screen level (zero parallax). Main functionality controls are grouped at the bottom and the left side (cf., Figure 7.8). This allows the HUD representation in front of the scene (in this case a driving scenario) to be the central element of the UI. The borders of the virtual HUD are visualized by a light gray line. New elements can be added to this area.

The S3D-HUD Designer supports working with elements on separate depth layers. On the left side, an overview of the existing layers is provided alongside the options to hide or rename layers. Below, the user can find a list of elements currently active on the selected layer. As an alternative, users can work in what we call the “free-mode”. In this mode, elements can be freely moved in 3D space.

At the bottom part of the UI are elements which can be added to the HUD scene by means of a simple click. There are three different kinds of elements: 3D shapes, images, and text elements. The former are displayed as actual 3D representations, which help the user to easily differentiate the 3D shapes. The S3D-HUD Designer is bundled with a set of graphics often used in HUDs such as traffic signs and location markers. However, our software is also able to load user

Figure 7.8: The S3D-HUD Designer allows the user to create the spatial layout of a HUD in front of a static 3D scenario.

defined images that can then be added to the HUD scene. The text tool allows textual information to be created, such as speed indicators or menu structures for infotainment purposes (e.g., a music player). By using the color panel on the left side, objects and text can be assigned a specific color and transparency. The 'Setting' control allows the created HUD to be observed in front of different 3D scenes. This functionality is helpful in judging HUD arrangements in multiple scenarios in the automotive context, for example, driving by night or driving on a freeway. We created several 3D photographs in side-by-side format using a 3D casing for two GoPro cameras and integrated these in our tool. In addition, our tool provides means to add further side-by-side images as 3D environment.

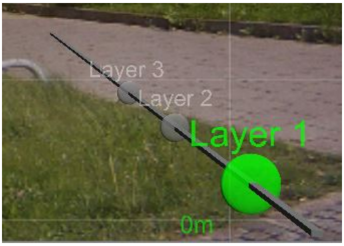

Figure 7.9: A dedicated control allows to precisely manage and overview current depth positions.

Depth Management

Our tool allows the organization of UI elements on layers. Starting the S3D-HUD Designer three default layers are activated. They are placed at a virtual distance of 0 m, 3 m, and 6 m, where 0 m is the projection distance (zero parallax). We recommend to use the tool with a viewing distance of 3 m. Users can add up to seven layers to be placed in the range of 1 m in front and 10 m behind the projection plane.

To position a layer at a particular depth, users are provided with a *depth controller* (cf., Figure 7.9). The currently active layer is highlighted and can be moved in z-direction by adjusting the depth controller. The depth layers can be deactivated for working in the free-mode. In this mode, the depth controller visualizes the currently selected objects instead of the layers. Elements can be freely positioned along all three axes. The depth of an object can be adjusted by either using the mouse wheel, gesture input, or the depth controller.

Additionally, we added means to control monocular cues in the free-mode. It allows dynamic size (objects appear smaller when distance is increased) and transparency (to simulate atmospheric haze) to be enabled or disabled.

Interaction

The standard form of interaction with the S3D-HUD Designer is using mouse and keyboard, following the suggestion of group B in the initial workshop. After defining the HUD's size, the user can add elements by clicking on the respective representation. The new element appears at the center of the HUD on the selected layer. To edit and transform an element, it must first be selected via mouse click. Multiple objects can be selected at the same time. The selected element(s) are highlighted with a green border (cf., Figure 7.8).

Elements can be translated in x, y, and z direction. While the free-mode allows the free positioning along all three axes, the layered-mode defines the z location of an element by the position of its respective layer. For rotation and scaling, we included a *transform* control panel. The user can select the operation (scaling or rotation) as well as the axes (x, y, z) to which this transformation should apply. If a cube is to be scaled in size, all axes must be selected to preserve the aspect ratio. After choosing the correct settings, the transformation can be executed by moving the mouse with pressed right button. Rotation was realized as a relative transformation. The initial mouse position is regarded as starting point. The larger the distance to this point, the faster the rotation.

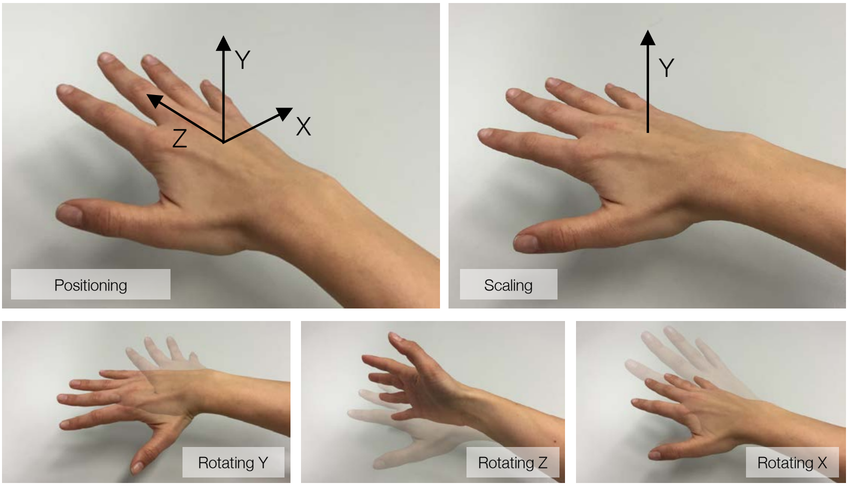

Figure 7.10: Gesture set for positioning, rotating, and scaling objects.

The alternative to mouse/keyboard interaction are mid-air gestures. To implement this we used the Leap Motion Controller[30]. We applied gesture interaction for positioning, rotation, and scaling. We implement dedicated keys to start the hand tracking so that it can not be activated accidentally. With one hand, users can press the activation key while the other hand is operating above the Leap Motion sensor. Interaction with the virtual elements is designed to match real world interactions (cf., Figure 7.10). To change the position of an element, the hand can simply be moved into the desired direction. The selected object in the S3D-HUD Designer is translated as if connected to that hand. Scaling is achieved by moving the hand along the y-axis. A movement away from the sensor increases the element's size, while a movement towards the sensor decreases its size. Rotation is realized by rotating the hand around the respective axis.

Implementation

The S3D-HUDD was implemented using the game engine Unity[31] with C# as script language. We decoupled the basic functionality, data storage, and user input. As a result, the software can be easily extended to support additional input devices in the future, such as Microsoft Kinect or eye trackers.

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[30] https://www.leapmotion.com/, last accessed October 13, 2015.

[31] https://unity3d.com/, last accessed October 19, 2015.

To process the raw data from the Leap Motion Controller, we used a Unity Asset provided by Leap Motion Inc[32]. For generating the necessary side-by-side output, we used the Unity Asset Stereoskopix FOV2GO[33] which arranges two separate cameras in a predefined interaxial distance and renders the image with a horizontal compression of 50%. As a result, our tool works with every stereoscopic display which supports compressed side-by-side images.

7.3.3 Evaluation

To evaluate the usability of the presented tool and to understand the effectiveness of the implemented interaction techniques, we conducted a user study with 24 participants. In particular, we were interested if the tool allows the comfortable and rapid prototyping of 3D depth layout concepts. Since the S3D-HUD Designer offers the user to interact with the mouse as well as 3D gestures, we explored which interaction method leads to a better performance in positioning, scaling, and rotation of objects in 3D space. Moreover, we evaluated if the management of the depth structure (freely positioning objects vs. organizing objects on depth layers) has an impact on the usability.

Study Design

The study is based on two independent variables with two levels each:

- **Interaction Technique:** Mouse input vs. gesture input
- **Depth Management:** Free-mode vs. layered-mode

We used a within subjects design resulting in four conditions per participant. We counterbalanced the order of the conditions applying a latin square.

Task

For each condition the participants had to complete the same five tasks in randomized order. The tasks required participants to position, rotate, and scale a circle object according to a defined target zone. Target zones were represented by spatially arranged rectangles. The circle and target were 2D objects since, first,

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[32] https://developer.leapmotion.com/downloads/unity, last accessed October 13, 2015.

[33] http://u3d.as/content/stereoskopix/stereoskopix-fov2go/2HA, last accessed October 13, 2015.

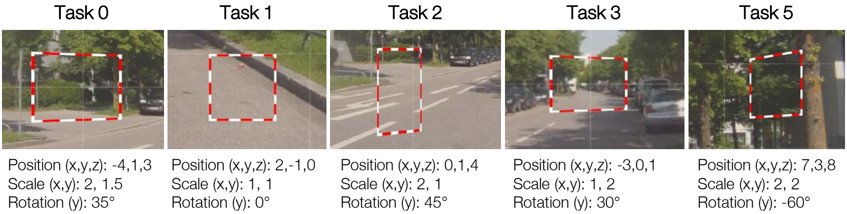

Figure 7.11: The target zones of the five tasks require the participants to position, rotate, and scale a circle object in accordance with the target zones.

we aimed at decreasing the complexity of the task and, second, automotive HUDs typically use 2D texts and graphics for unambiguous and simple visual feedback. Figure 7.11 shows the position, rotation, and size of the target zones. For each task, it was necessary to insert the circle into the scene, first, and then to arrange it according to the target. The initial position of the circle is the middle of the screen at zero parallax and the same for all five tasks. If the users were satisfied with the position of the circle, they pressed the space key of the keyboard to complete the task. Afterward, the participants could start the next task by pressing the space key again.

Measures

We collected objective as well as subjective data during the study. For the objective data, we measured for each task the TCT and the accuracy for positioning, rotating, and scaling the circle. The start and end point of the TCT is marked by hitting the space key. Regarding accuracy, we calculated three scores depending on the end transformation of the circle and the target properties as follows:

- The position score ($score_{pos}$) defines the length of the vector between the center of the target object (x', y', z') and the positioned circle (x,y,z):

  $$score_{pos} = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2} \tag{7.1}$$

  Note, that $score_{pos}$ cannot provide the accuracy of single axes but the total positioning accuracy in unity units.

- The rotation score ($score_{rot}$) calculates the difference of the rotation around the y-axis for the end rotation of the circle $rot_y(c)$ and the target $rot_y(t)$ in Euler angles (degrees):

  $$score_{rot} = |rot_y(t) - rot_y(c)| \tag{7.2}$$

Figure 7.12: The participants sat three meters in front of a 3D TV screen which showed the S3D-HUD Designer.

- The scale score ($score_{scale}$) is the difference between the areas of the end scale of the circle $(a*b)$ and the target object $(a'*b')$ in (unity units)^2:

$$score_{scale} = |(a*b) - (a'*b')| \tag{7.3}$$

For all accuracy measures, a lower score indicates higher accuracy. Besides the objective measures, we used subjective methods to evaluate the user experience and usability of the system. We applied the questionnaires AttrakDiff mini [89] and SUS [18] and conducted interviews with the participants while they explored the tool and its functions. In addition, the participants had to rank the four conditions from one (best) to four (worst).

Study Setup

Figure 7.12 shows the study setup. The study took place in a closed room at our lab to avoid any distraction. Participants were seated three meters in front of a 3D TV (Samsung UE55ES6300) visualizing the S3D-HUD Designer using shutter technology. On the table in front of them we positioned the input devices (i.e., keyboard, mouse, Leap Motion Controller). The Leap Motion Controller was placed in an *interaction box* (cf., Figure 7.13) showing the user in which range the device worked most accurately. Participants were allowed to arrange the devices in accordance with their preferences.

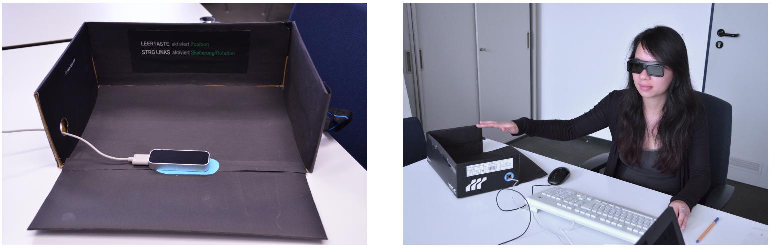

Figure 7.13: The participants used gesture interaction inside an interaction box indicating in which range the leap sensor works best.

The software of the S3D-HUD Designer ran on a ASUS G52JW notebook which transferred its graphical output to the 3D TV. The 3D TV received a side-by-side image and translated this picture to a stereoscopic image with a resolution of 1920x1080 using shutter technology. The shutter method required the participants to wear shutter glasses to perceive the stereoscopic effect properly. All participants that wore glasses confirmed that putting the shutter glasses on top of their glasses was not cumbersome nor uncomfortable.

Procedure

As participants arrived we introduced the study to them by giving a short introduction to S3D. Afterward, participants were seated in front of the 3D TV and conducted a stereo vision test using RDS [116] (cf., Appendix II). All participants passed the test and qualified for the study. Before introducing the S3D-HUD Designer, the different input devices were presented with focus on the Leap Motion since not all participants were familiar with this device.

The first part of the study consisted of an exploration of the tool's features and interaction modalities. Therefore, the participants had to solve simple tasks like inserting objects and text into the scene and manipulating its properties like position, rotation, scale, and color. Moreover, they explored the layered and the free-mode. While exploring the features of the system, the participants were motivated to think aloud and to reflect on their thoughts and impressions.

In the second part of the study, participants compared the two different interaction techniques as well as the depth management variants. For each of the four conditions the following procedure applied: First, participants were acquainted by completing a sample task. We instructed participants to solve the task as fast and as accurate as possible. The participants initiated each task by pressing the space

Figure 7.14: Means and standard errors as error bars for the ratings of the AttrakDiff.

key on the keyboard. After completing each of the four test tasks the participants completed the mini AttrakDiff and SUS. Subsequently, the next test condition started including the example (Task 0) and test tasks (Task 1–4).

After participants completed all four test conditions they were asked to rank the conditions according to their preference. An interview about the tool offered the possibility to reflect on its functions. Finally, a demographic questionnaire was filled in by the participants. One test session lasted about 60 minutes.

7.3.4 Results

In total, 24 participants (6 female, 18 male, P1–P24) aged between 21 and 53 years (M = 30.0, SD = 8.7) took part in this study. All of them worked in the automotive domain and were familiar with HUD technology. Their backgrounds range from psychology over interaction design to computer science. One participant stated to have no experience with 3D displays while five use stereoscopic displays several times per week or have intensive background on stereoscopic displays. The remaining 18 participants were acquainted with the stereoscopic effect by being exposed to it occasionally, for example in the cinema. In the following, we report on the subjective and objective findings of our study.

Subjective Results

Figure 7.14 shows the descriptive statistics of the mini AttrakDiff. It depicts that the mouse interaction outperforms gestures in regard to PQ and ATTR. Nevertheless, the gesture interaction slightly increases the HQ compared to mouse input. Looking at the depth management variants all three dimensions show

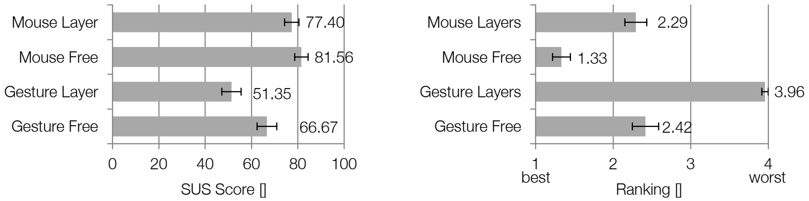

Figure 7.15: Means and standard errors as error bars for the ratings of the SUS (left) and the ranking of all conditions (right).

better ratings for the free-mode than the layered-mode. Regarding the AttrakDiff, a two-way ANOVA reveals statistical significances for all three dimensions: PQ, HQ, and ATTR. In detail, testing for PQ is statistically significant for the used interaction technique, $F(1,23) = 18.774$, $p < .001$, $\eta^2 = .449$, and depth management, $F(1,23) = 12.470$, $p = .002$, $\eta^2 = .235$, as well as for interaction technique * depth management, $F(1,23) = 11.918$, $p = .002$, $\eta^2 = .341$. In contrast, the dimension HQ solely shows a significant effect for the depth management, $F(1,23) = 9.365$, $p = .006$, $\eta^2 = .289$. The dimension ATTR reveals statistical significances for the interaction technique, $F(1,23) = 5.808$, $p = .024$, $\eta^2 = .202$, the depth management, $F(1,23) = 15.755$, $p = .001$, $\eta^2 = .407$, and their interaction, $F(1,23) = 4.832$, $p = .038$, $\eta^2 = .174$.

Analyzing the total score of the SUS yields similar results (cf., Figure 7.15). Mouse input significantly outperforms gestures, $F(1,23) = 22.139$, $p < .001$, $\eta^2 = .490$, and the depth management is improved for the free-mode compared to the organization in layers, $F(1,23) = 17.310$, $p < .001$, $\eta^2 = .429$. There is also a significant interaction effect, $F(1,23) = 12.879$, $p = .002$, $\eta^2 = .359$. A Friedman test reveals that the ranking is statistically significant, $\chi^2(3) = 50.950$, $p < .001$, to the advantage of mouse interaction in the free-mode. Figure 7.15 clearly depicts the inappropriate combination of gesture interaction and the layered-mode. Post-hoc Wilcoxon tests with Bonferroni corrections show that all pairwise comparisons are significant, $p < .007$, excluding the comparison of gesture interaction in free-mode and mouse interaction with layers, $p = .640$.

Regarding the tool in general, the interviews revealed that the S3D-HUD Designer is “useful” (P8) and allows to “easily generate spatial layouts” (P24). Seven participants stated that the UI is clearly structured. Especially, the design meets the requirements of simulating a HUD in the real world, as it provides the feeling of “looking through a window” (P2). However, some participants missed well known features of familiar prototyping and graphic programs. For instance, seven

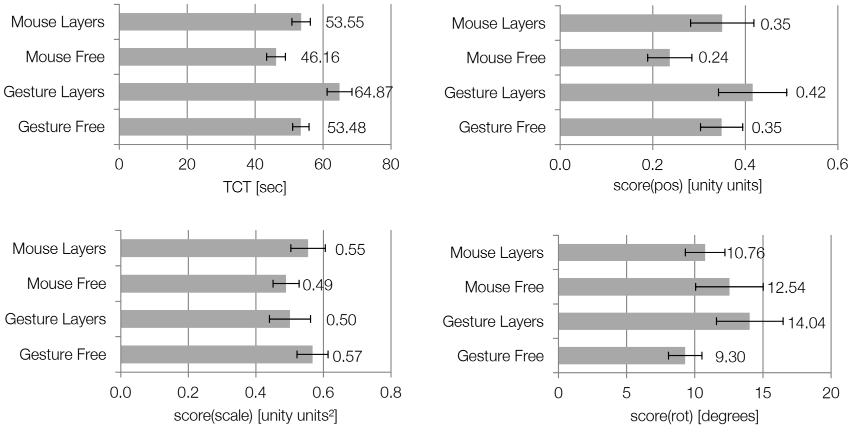

Figure 7.16: Means and standard errors as error bars for the objective data.

participants noticed the lack of an undo function and ten participants asked for a drag & drop function for adding elements to the scene. Moreover, one participant suggested to add a dialogue box for object settings to directly enter position, rotation, and scale values.

At the outset of the study, the participants welcomed the gesture interaction. Ten participants described the interaction as “cool” and “surprisingly easy”. After the second part, most of them (n = 8) revised that impression, because the interaction was not always ergonomic, especially for rotating objects around the y-axis. Moreover, the gesture interaction required many switches between the mouse and the Leap Motion Controller, for example, to activate scaling instead of rotating. As an improvement, three participants suggested gestures to define the axes to which the object transformation should be applied. In contrast, the participants described the mouse interaction as “better controllable”, “familiar”, and “precise”.

Objective Results

For all four tasks, we measured TCT as well as the accuracy of the object transformations. For analyzing the data, we aggregated the TCT as well as the accuracy scores for the test tasks per condition for each participant. Figure 7.16 shows the descriptive statistics for TCT, $score_{pos}$, $score_{rot}$, and $score_{scale}$.

Analyzing the TCT, the descriptive statistics reflect the outcomes of the subjective data. Gesture input results in an increased TCT and the free-mode decreases

TCT. A two-way ANOVA shows statistically significant main effects for the interaction technique, $F(1,23) = 30.466$, $p < .001$, $\eta^2 = .570$, and the depth management, $F(1,23) = 21.518$, $p < .001$, $\eta^2 = .483$, but there is no interaction effect, $F(1,23) = .673$, $p = .420$. Regarding $score_{pos}$, positioning the objects with the mouse is significantly more accurate than using gesture interaction, $F(1,23) = 8.113$, $p = .009$, $\eta^2 = .261$, while the variable depth management has no significant influence, $F(1,23) = 2.660$, $p = .117$, as well as the interaction technique * depth management, $F(1,23) = .498$, $p = .488$. Analyzing the data of $score_{rot}$ shows the most precise result for gesture input in the free-mode. However, there are no significant effects, neither for interaction technique, $F(1,23) = .001$, $p = .993$, nor for depth management, $F(1,23) = 1.276$, $p = .270$, nor for the interaction of both variables, $F(1,23) = 3.461$, $p = .076$. The analysis of the $score_{scale}$ data does not show significant effects, $p > .155$.

7.3.5 Limitations

Our study has the following limitations. First, we only tested a limited number of abstract tasks in order to decrease the complexity of the study. Hence, no conclusion can be drawn with regard to other tasks (such as alignment or grouping of objects) and their combinations. The tasks aimed at the evaluation of the interaction in 3D space rather than creating sophisticated UIs. Investigating such tasks could be subject to future work. Nevertheless, the chosen tasks required the participants to perform all transformation interactions positioning, rotating, and scaling at once. This leaves a thorough investigation of solely positioning, rotating, and scaling for future work to identify the proper interaction technique for the respective object transformation. Second, not all tasks were performed in all directions. For example, scaling was only done in the x- and y-dimension and rotation was only required around the y-axis. Future work could comprehensively assess all operations for all axes. Third, though we present findings on interacting with different depth management modes (i.e., the free- and the layered-mode), future studies could investigate how performance changes as users interact with more but one element at a time. In particular for multiple objects, the layered-mode may at some point outperform the free-mode.

7.3.6 Discussion

In summary, the exploratory think-aloud phase in the study as well as qualitative and quantitative findings suggest that the S3D-HUD Designer provides a high usability and allows S3D HUD prototypes to be created quickly and easily. This is particularly supported by the high SUS score in the free-mode with mouse input condition (> 80).

In regard to the input modality, mouse interaction was significantly faster than gesture interaction. Gesture input required to use the mouse as well to toggle between the transformation mode (i.e., positioning, rotating, scaling) and to select the dimensions (i.e., x, y, z). These modality switches between the leap sensor and the mouse not only impacted on TCT but also frustrated some of the users, resulting in lower subjective ratings. At the same time, gesture interaction tends to increase the accuracy for rotating the objects in the free-mode although participants stated that movements of the hand around the y-axis are uncomfortable and unergonomic. In order to reveal improvements in accuracy, we recommend to investigate gesture-based rotations around x- and z-axis since these poses of the hand might be more comfortable [127, 169]. To address the challenge of switching between mode and dimension in the future, the integration of further modalities, such as speech or gaze, can avoid moving the hand away from the controller.

We found that participants performed tasks more accurately in freely arranging objects and also reported on higher usability for the free-mode. Note, that a reason for this could be the fact that users worked with single objects only. The layered-mode may unfold its potential as the UI becomes more complex. In such cases, users may want to move a number of objects from one layer to another, which is well supported by the layered-mode. An interesting question in this context is also, whether clusters of elements with a relationship should be structured according to their depth position (depth layers with important information displayed in the foremost layers) or based on proximity when referencing a real world object in the environment (the correct x-, y- and z-position plays a major role). While for the first case the layered-mode seems to be more appropriate, the free-mode may better support the latter use case.

7.4 Summary

In this chapter, we presented two tools, the *S3D-UI Designer* and the *S3D-HUD Designer*. The tools are meant for designers who want to quickly and easily create early digital UI prototypes for 3D displays. We developed both tools based on initial expert workshops and evaluated them in comprehensive user studies. The development process as well as the final evaluation of the tools led to four major principles that computer-based prototyping tools for 3D displays should consider:

- **Enable instant visual feedback of the 3D layout.** The interplay of the prototyping tool and the resulting 3D output needs to be seamless to decrease interaction steps for checking the stereoscopic results. We applied two approaches to fulfill this requirement. The S3D-UI Designer incorporates a 2D display for designing the UI and its layout while a 3D output device instantly visualizes the stereoscopic representation. In contrast, the S3D-HUD Designer uses one 3D display to visualize the controls of the prototyping tool as well as the prototyped S3D interface. We recommend the first approach for prototyping abstract UIs that use 3D to structure content while the second approach supports virtual, mixed, and augmented reality applications that involve virtual or real 3D environments.

- **Focus on 3D layout features.** Prototyping tools for 3D UI layouts should focus on the arrangement of objects in space. Hence, the tools aim at supporting the user in choosing the correct stereoscopic parameters, providing means for managing monocular cues and design aids for 3D layouts (e.g., reference lines in space or highlighting occluded objects). In contrast, these tools should not incorporate complex design features provided by professional graphic software as Blender or Photoshop and instead include basic features for editing objects. In this way, the design of the GUI elements, their spatial layout as well as the application logic can be separated and developed in parallel.

- **Adapt 2D GUI concepts for 3D interaction.** Interaction in 3D space is challenging. We recommend to adapt well-known 2D concepts to design stereoscopic UIs. One approach is to restrict the 3D design space to several 2D depth layers which can be arranged along the z axis. Another approach is the free manipulation and positioning of elements in 3D space by using well-known 2D interaction devices such as keyboard and mouse. The final evaluation of the S3D-HUD Designer reveals that mouse interaction outperforms mid-air gestures for these interactions since the mouse is a well used and trained interface. Nevertheless, the fact that gesture interaction tends to increase the precision for rotating objects is promising.

- **Consider different working environments.** Finally, the working environment in which the tool is used has a significant influence on the prototyping process. While a desktop setting maximizes the usability of the tool, interactive tabletops invite to explore ideas in a group collaboratively.

The presented tools focus on prototyping the 3D visualization of the UI instead of supporting the creation of interactive 3D prototypes. Further refinements of the tools can incorporate the prototyping of simple user interactions as well as dynamic visualizations by means of animations. Particularly, the reasonable visualization of transitions between system states and object movements in 3D space need to be carefully designed to foster the users' cognitive map of the UI. In the next part, we present interactive stereoscopic prototypes of an automotive IC and evaluate the use of the stereoscopic effect in driving simulator and real world environments.

V

AUTOMOTIVE
APPLICATION DOMAIN

OUTLINE

Stereoscopic visualizations provide the opportunity to design new information layouts for in-vehicle UIs. However, the immersive 3D experience as well as potential stereoscopic artifacts can negatively influence the driving behavior. The potentials and risks of stereoscopic visualizations require a thorough investigation for the complex domain of automotive UIs.

In this part, we present S3D prototypes and evaluate the use of stereoscopy for designing automotive instrument clusters (ICs).

- **Chapter 8 – Manual Driving in the Simulator.** Stereoscopic displays provide challenges but also opportunities for visualizing an automotive IC. In this chapter, we present a prototype of a stereoscopic IC for manual driving. We evaluate the influence of the 3D effect on secondary and primary task performance by means of a driving simulator study.
- **Chapter 9 – Manual Driving in the Real World.** In order to complement and extent our findings in the simulator, we equipped a vehicle with a stereoscopic instrument display. We used this test vehicle for two real-world driving studies, one with experts in automotive UIs using an heuristic evaluation approach and one with non-experts.
- **Chapter 10 – Highly Automated Driving.** With the advent of highly automated driving the requirements of in-car applications shift. In this chapter, we initially explore the effect of using a 3D application while highly automated driving when the vehicle initiates a take-over request. We compare the take-over behavior of the driver previously interacting with a pure 2D application against using a 3D visualization incorporating binocular as well as monocular depth cues.

Chapter 8

Manual Driving in the Simulator

Stereoscopic displays are quickly proliferating in our everyday life. Having been a technology mainly used in the entertainment sector over the past years, the advent of commercial autostereoscopic devices may soon make this technology ubiquitous. Particularly, the automotive industry takes notice of this development. For example, Mercedes integrated a stereoscopic instrument cluster (IC) into their concept car F125[34] and Jaguar Land Rover[35] presented a stereoscopic display as IC to facilitate the judgment of spatial relations. Car manufacturers know that stereoscopy creates an immersive and impressive experience. As a result, showing such concept cars can possibly raise their publicity as innovation drivers. However, using the S3D effect for presenting information while driving a car requires a thorough evaluation to avoid accidents due to a distracted driver and to ensure benefits of this particular type of visualization.

3D displays provide novel means to display information that can enhance the human-machine interaction (HMI). In particular, stereoscopic visualizations can add several semantics to information presented in an abstract form (e.g., icons,

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[34] http://www.pocket-lint.com/news/112047-mercedes-benz-f152-concept-car-video, last accessed Oktober 7, 2015.

[35] http://newsroom.jaguarlandrover.com/en-in/jlr-corp/news/2014/07/jlr_virtual_technologies_100714/, last accessed October 7, 2015.

warnings). Hence, information can be positioned in a way that allows users to quickly and accurately perceive the priority of UI elements – more important information is visualized in the front while content with lower priority is visible further away. Furthermore, the third dimension can be exploited to represent the spatial relationship between items – the distance between two elements shows how far two events are apart, time-wise and location-wise. For example, a navigation system can communicate the distance to the next exit on the current highway based on depth information. As the driver is mainly engaged in the primary task of driving a car such an interface may be useful to communicate information in a subtle and unobtrusive way. Nevertheless, the immersive character of stereoscopic visualizations [263] as well as possible visual discomfort and fatigue [129] can distract the driver. So far it is unclear how the interaction with stereoscopic UIs impacts drivers as well as their visual and cognitive workload level.

As a result, we investigate how S3D UIs influence the primary and secondary task performance of the driver. This is crucial in cars, since the driver's attention towards the display needs to be minimized and the required information should be perceived immediately. We present a driving simulator study which evaluates the visual and cognitive load implied by the use of 3D displays. We focus on primary (driving) and secondary tasks to reflect different attention levels.

First, we created a 3D digital IC. The design is based on the design principles we extracted from our initial studies presented in Part III. The IC is able to communicate various types of information. Besides driving-relevant information, such as the current speed, the IC provides traffic information, warnings, distances, and driving instructions. Second, we conducted a user study in a standardized driving scenario where users needed to respond to expected and unexpected events. We compared a monoscopic (2D) against a S3D visualization, interfaces of different complexity (low vs. high amount of information), and different stereoscopic display technologies (shutter vs. autostereoscopy). For each participant, we measured primary and secondary task performance, as well as the subjective perception of the UI (discomfort, workload, attractiveness). The results show that the well-considered use of stereoscopy is well suited for secondary tasks while driving a car. We did not only find an increase in accuracy for judging the distance to a UI object (for expected events), but also that TCT decreases for responding to unexpected events (e.g., warnings). We could not find a significant impact of S3D on the driving performance, compared to the standard 2D UI. However, there is a significant influence of the used display technology. Finally, subjective feedback reveals that participants favor the S3D visualization of the IC over its 2D version.

This chapter is based on the following publication:

- N. Broy, F. Alt, S. Schneegass, and B. Pfleging. 3D Displays in Cars: Exploring the User Performance for a Stereoscopic Instrument Cluster. In *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI ’14, pages 1–9, New York, NY, USA, 2014. ACM

8.1 Related Work

First experiments in 3D visualizations for automotive UIs aim at comparing monoscopic spatial presentations against pure 2D display layouts [29]. They show that a spatial representation (using monocular cues) is preferred by the users, due to an increased joy of use and usability. In addition, it reduces the TCT for short tasks compared to 2D list-based UIs. Regarding autostereoscopic 3D displays, Krüger found that such displays require longer attention spans and they were not considered being more attractive than traditional displays for the use case of ACC [128]. However, we assume that the 3D quality which depends on the display technology as well as the content design has a major impact on user performance and experience. High quality stereoscopic visualizations were shown to support prioritizing the foremost content and to increase the perceived quality of an IVIS [22].

Recently, a research interest in S3D ICs emerged. Szczerba and Hersberger [230] used a autostereoscopic display (parallax barrier) to investigate visual search and change detection of check controls in a stereoscopic instrument display. They used two depth planes: one in front of the screen (with a negative disparity of 6 arc-min resulting in 10 mm in front of the screen plane) displaying check controls and one on the screen plane depicting the other elements of the IC in 2D. A laboratory study reveals that stereoscopy improves visual search times when the target is absent while there is no difference between 2D and 3D for searching present targets. Since the check controls are coded by shape, color, and size, those features seem to outperform stereoscopic depth. Nevertheless, the study shows that stereoscopy increases the user performance to detect changes in the displayed check controls for small set sizes (1–3 check controls). Although Szczerba and Hersberger [230] investigated a high-fidelity prototype of an automotive IC they did not involve a driving task. In contrast, Pitts et al. [182] investigated the stereoscopic effect in a driving simulator study showing three horizontally aligned rings in the instrument display. They highlighted one of the three rings using low and high parallaxes or solely monoscopic depth cues. Their results show that stereoscopy increases performance in identifying the highlighted object and reduces eye-off-the-road time. But Pitts et al. did not visualize informative content which is typically displayed by an automotive IC.

The results of Szczerba and Hersberger [230] and Pitts et al. [182] constitute basic findings that need further refinements with high-fidelity prototypes in driving environments. This motivated us to investigate the potentials offered by a S3D IC in a driving simulator study.

8.2 Driving Simulator Study

In order to investigate the impact of stereoscopic visualizations while driving a vehicle, we conducted a driving simulator study with 56 participants. The goal of this study is to identify potentials as well as risks that come along with stereoscopic UIs in cars. By applying the tools presented in Part IV, we developed an automotive IC that uses stereoscopy to structure its content. The design of the interface meets the requirements explored in Part III in order to evaluate the full potential of a stereoscopic UI. Otherwise, we are confident that uncomfortable stereoscopic settings would obviously result in a decrease in primary and secondary task performance.

8.2.1 Hypotheses

In the following, we present our hypotheses which are clustered according to three main aspects, which are the general influence of a stereoscopic visualization, the interface complexity in terms of information load, and the used display technology.

Influence of 3D Visualization

First, we assume differences inferred by the 3D visualization chosen for presenting the UI. Usually, UI designers need to make a choice whether to create a monoscopic or a stereoscopic visualization – independent of how it is later presented technically. Based on prior findings (cf., Szczerba and Hersberger [230], Pitts et al. [182], and Section 5.3 of this thesis), we hypothesize that a 3D visualization has a positive effect on secondary task performance as well as on user experience compared to a monoscopic visualization. At the same time, we expect an influence on the primary task performance, the time users take their eyes off the road and on the driver activity load. However, it is uncertain if this influence is positive or negative. On the one hand, 3D displays may support the driver in the primary driving task by making relevant information easier perceivable and, thus, decrease the load for assessing the information. On the other hand, AC mismatches and visual artifacts affect the user's comfort state [129] and can in turn negatively influence the driver's cognitive load and primary task performance. Apart from this, following the multiple resource theory of Wickens [251] the S3D presentation of the IC as well as the driving task address both visual-spatial resources. In consequence, the increased interference can decrease primary driving task performance, due to an increased workload level. In addition, the immersive nature of 3D presentation might tempt the driver to rest with the visual attention on the IC. We assume that the arguments for a decline in primary task performance outweigh the positive aspects of S3D on the driver's workload level. As a result, we expect that S3D increases visual load and hampers driving performance.

- H1-UX: The driver rates the attractiveness and user experience of the UI higher when interacting with a S3D visualization.
- H1-STJ: The judgment of distances for a secondary task occurs more accurate when interacting with a S3D visualization.
- H1-STH: The reaction on highlighted instructions occurs faster when it is highlighted by a S3D effect.
- H1-PT: The primary task performance decreases when interacting with a S3D visualization.
- H1-G: The eyes-off-the-road time increases when interacting with a S3D visualization.

Influence of Complexity

Second, we investigate the visual complexity of the UI. Whereas in traditional instrument displays most elements are hard-wired limiting the way in which the available space could be used, digital displays allow the dynamic visualization of any information available in the car. Hence, designers of digital in-car UIs may be intrigued to display as much information as possible. However, we hypothesize that this overload leads to a decrease in user experience, primary, and secondary task performance and increases the time users do not look on the road as well as the driver's workload. However, stereoscopy has the ability to declutter visual content [179, 197] and can possibly reduce the complexity of displays with a high information load.

- H2-UX: The user experience decreases when the driver is confronted with a high information load displayed in the IC.
- H2-ST: The performance in secondary tasks declines when the IC displays a high amount of information.
- H2-PT: The primary task performance decreases when the IC displays a high amount of information.
- H2-G: Eyes-off-the-road time increases when the driver is confronted with a high information load displayed in the IC.

Influence of Technology

Third, we investigate the influence of the used display technology. Whereas we consider a 2D screen, today commonly found for digital ICs, as a baseline, we are particularly interested in comparing two S3D technologies: glasses-based technologies (i.e., active shutter) and glasses-free technologies (i.e., autostereoscopic displays). We hypothesize that autostereoscopy decreases user experience and secondary task performance since autostereoscopic technologies strongly lacks in 3D quality compared to shutter. In contrast, we think that shutter has a negative impact on the primary task performance since the required glasses are disturbing and darken the view.

- H2-UX: The user experience increases when interacting with a shutter display technology which provides a high 3D quality.
- H2-ST: The secondary task performance declines when interacting with an autostereoscopic display with reduced quality for the S3D visualization.
- H2-PT: The primary task performance declines when a shutter display is used.

8.2.2 Prototype and Study Setup

In order to evaluate our hypotheses, we equipped a basic vehicle mockup with a construction that allowed us to use various notebook monitors as IC display.

Figure 8.1: We used a mid-fidelity driving simulator to evaluate the influence of a 3D visualization, the display technology, and the interface complexity on user performance and subjective perception.

Vehicle Mockup and Driving Simulator

The vehicle mockup consisted of an adjustable driver seat, a multifunctional steering wheel, as well as accelerator and brake pedals. Although we used a very basic mockup the average size of notebooks did not allow their simple positioning behind the steering wheel in order to simulate the IC. As a result, we installed a bracket which mounted the notebook in a 45 ° angle behind the steering wheel with the notebook's display facing downwards. A surface-coated mirror was mounted on the keyboard of the notebook to reflect the displayed content to a vertical layer behind the steering wheel (cf., Figure 8.1). Thus, the participants could see the displayed image at a position common for an IC. Moreover, this setup allowed the simple modification of the display hardware. We applied two display variants in our user study. Both were the monitors of notebooks. To test a glasses-free technology, we used the lenticular autostereoscopic display built-in a Toshiba Notebook P855-107. The 15.6" display had a resolution of 1366 x 768 in 3D mode and 1920 x 1080 in 2D mode. The display was equipped with a tracking unit that adjusts the viewing angle based on the viewer's position. However, our setup did not allow us to make use of this feature. As a consequence, participants had to adjust their seat in a way to comfortably maintain the sweet spot of the autostereoscopic display. As a glasses-based technology, we used the shutter display of an ASUS notebook G75VW equipped with Nvidia 3D Vision. This display had a screen size of 17.3" and a resolution of 1920 x 1080. The 3D quality of the shutter display was very high due to the good separation of left and right eye image and a full HD resolution in 3D mode.

The notebook displaying the IC was connected via Ethernet to the driving simulation, which enabled a two way communication between the IC application and the simulation. A third node in this network was a notebook which was responsible for the tracking of the user's gaze path for our study. As tracking device we used the Ergoneers' Dikablis[36] glasses-based eye-tracker. This configuration enabled a synchronized logging of the driving, gaze, and secondary task data. The simulation depicted the driving scene on a 52 " LCD monitor with full HD resolution (i.e., 1920 × 1080 pixels) at 60 Hz. During the study, participants sat 2.5 meters in front of the driving scene and approximately 75 cm away from the screen plane of the reflected IC.

S3D Instrument Cluster

We used Unity[37] with C# as scripting language to build the interactive IC. For the purpose of our study, we integrated elements that take advantage of 3D space. Thus, we applied elements exploiting the spatial relationship between objects (e.g., a navigation system showing upcoming maneuvers) and elements representing unexpected events (e.g., a warning that requires immediate action). Furthermore, the design of the IC uses the available 3D space in order to structure the displayed information reflecting their current importance. Figure 8.3 outlines the spatial structure of the IC as well as the applied parallax range. In the following, we present the used UI elements and their layout in 3D space:

Abstract Driving Space: The abstract representation of a street shows upcoming events such as navigation cues, traffic signs (speed limits), and traffic

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[36] http://real.psych.ubc.ca/images/9/9b/SW_Dikablis_Handbuch_V2.0_ENG.pdf, last accessed September 4, 2015.

[37] https://unity3d.com/, last accessed October 19, 2015.

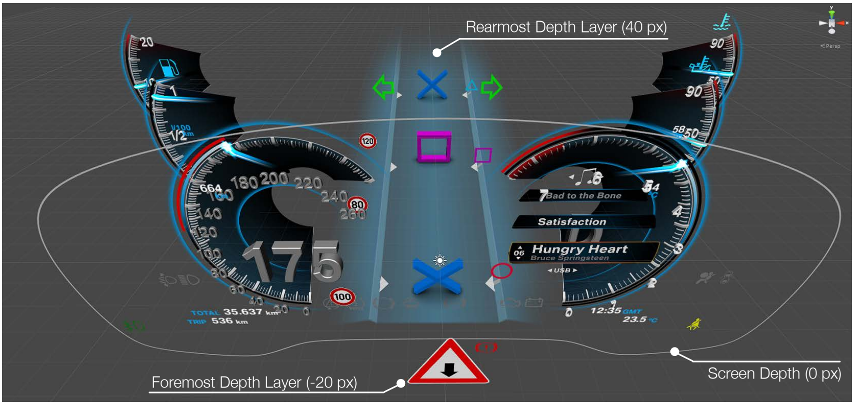

Figure 8.2: This top view of the implemented concept depicts the spatial arrangement of the displayed IC elements. The parallax values used for the shutter representation are given in brackets.

information (traffic jam). The depth position of the events inside this virtual space correlates with the actual distance from the vehicle. The *abstract driving space* occupies the depth range from the screen plane to the maximum positive parallax. We used smaller parallax values for the presentation of the scene using the autostereoscopic display to reduce crosstalk. While the maximum positive parallax is 40 pixels for the shutter setting, we applied just 9 pixels for the autostereoscopic display.

Warnings: We integrate pop-up instructions showing urgent information the driver has to take immediately into account (e.g., collision warnings). The warning appears in front of the screen plane in order to emphasize urgency. The used negative parallax was -20 pixels for the shutter and -5 pixels for the autostereoscopic display.

Speed and RPM Gauge: On the left side of the abstract driving space, we visualize the speed with a gauge and a digital number in the center. The current speed limit is visualized at the border of the gauge with a green and red bar. In order to maximize the readability of the speed information as this is the most important driving information, the numbers of the gauge are displayed at screen depth. At the right side of the abstract driving space, the IC displays the rpm and the current gear in the center. It exhibits the same depth layout as the speed gauge.

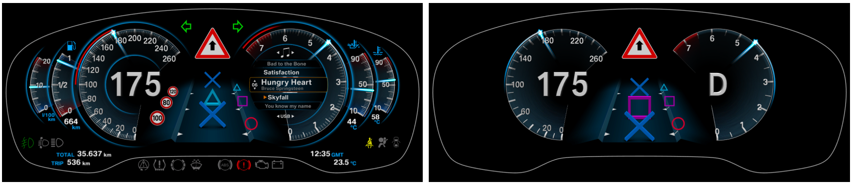

Figure 8.3: The left image depicts the high complexity layout of the IC while the right picture shows the low complexity layout.

Temperature and Fuel Gauge: There are four more gauges that depict current fuel consumption, remaining fuel, oil temperature, and cooling water temperature. These gauges are arranged on layers behind the speed and the rpm gauge.

Check Controls: We include both active and inactive check controls close to the screen layer. Active check controls are placed at screen depth whereas inactive check controls are shown greyed out and positioned slightly behind the screen layer.

Board Computer: Our concept shows additional status information such as time, outside temperature, as well as the trip and total kilometers of the odometer.

Infotainment: In addition, our IC provides a small infotainment menu (cf., a music list). If the user is interacting with the infotainment system, for example by switching the current music track, the list pops up in the center of the rpm gauge and highlights the currently selected title.

To investigate the influence of UI complexity, we implemented two IC variants (cf., Figure 8.3). The first version depicts all UI elements described above. The second one shows a reduced information space which solely depicts the most important elements (abstract driving space, warnings, speed and rpm gauge). Please refer to Appendix V to get an impression of the S3D layout of the IC.

8.2.3 Tasks

During the study participants performed a primary driving task (i.e., controlling the car) and a secondary task (i.e., reacting to expected and unexpected events). As primary driving task we used the following headway scenario based on the

Principle 2.1B of the AAM [1] and the visual manual NHTSA driver distraction guidelines [166]. The task required the participants to follow a white vehicle on the right lane of a three-lane motorway. They were told to keep the same speed as the car in front (100 km/h) and to maintain a constant distance of 50 m. Figure 8.4 depicts the driving task from a bird's-eye view.

The secondary task was to estimate the depth relation of objects in the abstract driving space. In the remainder, we call this the depth judgment task. Symbols with varying shapes (circle, square, and triangle) appeared at the end of the street and moved towards the driver. For each symbol type a static "target zone" was marked with white arrows on the street (cf., Figure 8.3) – the symbols on the right indicate the corresponding symbol type. When the symbol reached its target zone (same depth position), the participant had to push a button 'X' on the steering wheel (cf., Figure 8.4). If the button was pressed, the symbol disappeared. When a new symbol appeared, the system provided an auditory cue to make the driver aware of the new task. Hence, the participants were aware that an upcoming event is active. We refer to these events as expected events. To make the task more difficult, the IC showed cross symbols as distractors beside the three symbol shapes. We chose this task because it requires frequent glances at the IC to check the current symbol positions.

Participants were also required to react to unexpected events. Therefore, the IC showed a large icon with an arrow pointing upwards or downwards (cf., Figure 8.3). According to the direction, participants should push the corresponding direction of a toggle button on the right side of the steering wheel (cf., Figure 8.4). We instructed the participants to react as accurate and fast as possible on these unexpected events. These events only appeared if the depth judgment task required an interaction. This constraint made sure that the participant's eyes were on the display when the warning appeared. Thus, effects of focus switches could be eliminated. In the following, we refer to this task as warning task.

8.2.4 Study Design

We used a mixed study design. Therefore, we applied two within variables and one between factor:

- **Visualization (within):** We presented participants a monoscopic (*2D*) and a stereoscopic (*3D*) visualization as within factor.

Figure 8.4: For the primary task the participants followed a white vehicle on the right lane (left picture). We tracked the gaze behavior while driving (middle picture). For the secondary task (right picture) a button 'X' on the left side of the steering wheel needs to be pressed for judging the position of symbols. A toggle button ('↑' or '↓') on the right side of the steering wheel decodes the reaction on unexpected events.

- **Complexity (within):** To evaluate the influence of information complexity on the visualization we distinguished two variants. One showed all IC elements, providing a *high* visual complexity. The other one solely showed the IC elements that are necessary to solve the primary and secondary tasks (*low*). The participants experienced both levels of information complexity during the study.
- **Technology (between):** We used two display technologies in the study as between factor. One half of the participants solved the tasks on a *shutter* display, which required 3D glasses but provided a high 3D quality. To assess comparable results, the participants using the shutter display wore the active shutter glasses during all conditions even for the monoscopic ones. The other half of the participants used an autostereoscopic display (*autostereoscopy*) that lacked in 3D quality in terms of resolution and 3D artifacts such as crosstalk.

Each within factor has two levels resulting in four within conditions. As a result, we conducted four test drives (one for each within condition) with every participant. We counterbalanced the order of the four within conditions using a latin square. Per condition we showed each symbol of the depth judgment task ten times. In addition, we added two depth judgment tasks for each of the three symbol types that trigger an unexpected event, one with an arrow pointing up and one with an arrow pointing down. As a result, one condition contained $3 \times (10+2) = 36$ tasks. The task order was randomized.

8.2.5 Procedure

Participants were recruited through mailing lists. As they arrived in the lab we introduced the study procedure and provided a brief explanation about S3D. Participants first completed a stereo vision test based on RDSs (cf., Appendix II) to qualify for the study. After completing a demographic questionnaire, the participants started with the first drive. This drive did not require to cope with secondary tasks to get familiar with the driving simulator. As soon as the participants felt comfortable with the driving task and controls, we introduced the secondary tasks. After we instructed the participants on how to react to appearing symbols and warnings, they practiced the reaction on 30 depth judgment and six warning tasks. Subsequently, the first of four test conditions started. During the conditions, participants had to complete the primary driving task and the secondary tasks simultaneously. For each test drive 30 depth judgment and six warning tasks appeared with a preceding training block of five depth judgment and four warning tasks. In total, each participant completed $5+4+30+6=45$ secondary tasks for each test drive. The task sequence started at a specified point on the test track that allowed the participants to accelerate up to the required 100 km/h and to find a constant distance of 50 meters to the car in front. Each test drive lasted about 12 minutes and was followed by completing additional questionnaires. Finally, participants ranked the four conditions due to their preference and had the possibility to comment on the 3D effect and the information complexity. The study took about 90 minutes.

8.2.6 Measures

We used objective and subjective measures to assess user performance, visual and cognitive load, as well as user experience.

Primary Driving Task Performance

We measured the driving performance by logging the data of the driving simulation with a frequency of 50 Hz. We considered the *longitudinal control* by measuring the standard deviation of the distance gap, that is, the distance between the rear-most surface of the lead vehicle and the forward-most surface of the following vehicle as defined in the SAE standard J2944 [199]. We evaluated the *lateral control* by measuring the standard deviation of the lateral position from the vehicle center to the right lane border.

Secondary Task Performance

For measuring the performance for the depth judgment tasks, we logged the distance between the actual position of a symbol and its respective target zone at the time when the participant pushed the left steering wheel button. We analyzed the means (*mean distance*) and standard deviations (*SD distance*) for the distance between symbol and target zone. For the warning tasks (unexpected events), we assessed *TCT* (i.e., the time between presenting the stimulus and the participant pushing the toggle button) and *error rates* (i.e., percentage of incorrect responses). The data was logged on the notebook which served as the IC display with a frequency of 60 Hz.

Gaze Data

For the autostereoscopic group we used a head-mounted eye tracker to track gaze. Since the shutter group wore 3D glasses the use of the head-mounted eye tracker was not possible for them. We calculated the *mean glance duration* on the IC (mean eyes-off-the-road time) as well as the *total number of glances* onto the IC for solving the tasks. The gaze data was logged with a frequeny of 50 Hz.

Subjective Measures

We used three questionnaires which the participants completed after each of the four test drives. To measure the intuitiveness of the interaction with the UI, we used selected measures of the INTUI questionnaire [237]. We asked about *Effortlessness (E)*, *Gut Feeling (GF)*, and *Magical Experience (ME)*. Participants filled in a DALI questionnaire [178]. Using the proposed weighting procedure, a total score was calculated per condition that combines the ratings of the different workload aspects. To investigate details about simulator sickness, we applied the SSQ [120]. At the end of the study, the participants ranked the four conditions from one (best) to four (worst).

8.3 Results

In total, 56 participants (11 female, 45 male) aged between 20 and 59 years ($M = 32.75$, $SD = 8.96$) took part in this study. All had normal or corrected to normal visual acuity and passed the stereo vision test. Ten participants never experienced stereoscopic visualizations before while the remaining 46 participants

Table 8.1: Descriptive statistics (mean and standard deviation in brackets) for all measures and conditions. Note, that measuring the gaze data was not possible for the shutter technology.

Measure	**Autostereoscopy**				**Shutter**			
	Low 2D	Low 3D	High 2D	High 3D	Low 2D	Low 3D	High 2D	High 3D
Lateral Control [m]	0.047 (0.016)	0.048 (0.013)	0.050 (0.021)	0.051 (0.023)	0.057 (0.017)	0.059 (0.016)	0.059 (0.015)	0.061 (0.017)
Longitudinal Control [m]	0.573 (0.290)	0.564 (0.296)	0.739 (0.418)	0.636 (0.327)	0.672 (0.314)	0.609 (0.327)	0.711 (0.391)	0.676 (0.346)
Mean Dist. [Unity Units]	0.907 (0.221)	0.885 (0.293)	0.956 (0.403)	0.897 (0.315)	0.874 (0.300)	0.718 (0.285)	0.967 (0.346)	0.688 (0.241)
SD Distance [Unity Units]	0.687 (0.246)	0.569 (0.189)	0.805 (0.564)	0.646 (0.287)	0.577 (0.234)	0.558 (0.294)	0.653 (0.249)	0.531 (0.171)
TCT [s]	1.150 (0.123)	1.126 (0.149)	1.168 (0.220)	1.137 (0.148)	1.182 (0.227)	1.137 (0.149)	1.190 (0.149)	1.132 (0.137)
Error Rate [%]	0.595 (3.150)	2.08 (6.26)	1.190 (4.371)	2.976 (10.197)	1.190 (6.299)	1.190 (4.371)	2.381 (5.939)	2.381 (5.939)
Mean Glance Duration [s]	0.860 (0.236)	0.907 (0.278)	0.853 (0.264)	0.914 (0.250)	-	-	-	-
Total No. of Glances []	172.11 (32.249)	167.54 (32.256)	169.21 (33.111)	168.00 (30.985)	-	-	-	-
INTUI (E) []	4.829 (0.811)	5.021 (0.647)	4.650 (0.796)	4.879 (0.702)	4.893 (1.175)	5.057 (1.020)	4.486 (1.067)	4.529 (0.976)
INTUI (GF) []	3.536 (1.060)	3.821 (1.128)	3.696 (1.048)	3.589 (1.218)	3.670 (1.231)	3.527 (1.193)	3.884 (1.181)	3.652 (1.233)
INTUI (ME) []	3.795 (0.988)	4.420 (1.099)	4.045 (1.067)	4.598 (1.246)	3.652 (1.135)	4.759 (1.060)	4.018 (1.069)	5.027 (0.840)
DALI (Total Score) []	40.918 (16.238)	42.041 (19.045)	40.000 (18.335)	43.979 (18.797)	37.143 (21.451)	40.510 (20.500)	39.082 (22.009)	42.551 (20.928)
SSQ (Total Score) []	12.823 (16.204)	12.021 (14.480)	11.487 (11.513)	11.086 10.254	10.151 11.599	10.953 (12.380)	10.552 (10.871)	12.155 (18.084)
Ranking []	2.750 (1.175)	2.071 (0.940)	2.714 (0.897)	2.464 (1.347)	3.000 (0.861)	1.679 (0.772)	3.321 (.819)	1.929 (1.016)

knew the effect from cinema. Half of the participants (7 female, 21 male) aged between 21 and 49 ($M = 32.96$, $SD = 7.58$) used the autostereoscopic display while the other 28 participants (4 female, 24 male) aged between 20 and 59 ($M = 32.54$, $SD = 10.29$) drove with the shutter technology. In the following, we present the results of our study. Table 8.1 shows all means and standard deviations of the applied measures.

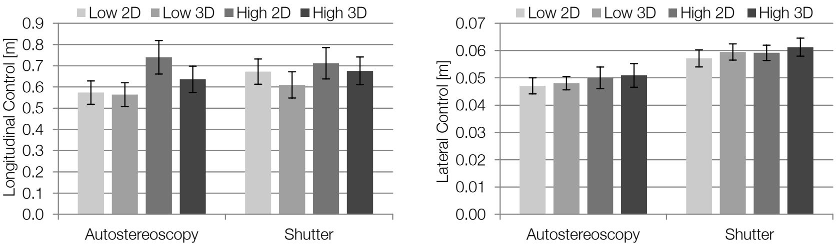

Figure 8.5: Means and standard errors as error bars for the primary task measures, lateral and longitudinal control.

8.3.1 Primary Task Performance

Figure 8.5 shows that the longitudinal control seems to improve for using the 3D visualization while the lateral control improves for the monoscopic visualization. However, testing 2D against 3D using a mixed ANOVA shows no statistically significant differences for both longitudinal control, $F(1,54) = 2.869$, $p = .096$, and lateral control, $F(1,54) = 2.297$, $p = .135$. Looking at the information complexity, longitudinal as well as lateral control is increased for the IC with a high information load. This difference is statistically significant for the longitudinal control, $F(1,54) = 5.917$, $p = .018$, $\eta^2 = .10$, but not for the lateral control, $F(1,54) = 2.353$, $p = .131$. While the used display technology has no influence on longitudinal control, $F(1,54) = .296$, $p = .588$, the autostereoscopic sample performed significantly better in terms of lateral control than the shutter sample, $F(1,54) = 6.102$, $p = .017$, $\eta^2 = .10$. Looking at the interaction of the independent variables, we could not find any significant effect for both measures (i.e., longitudinal and lateral control), $p > .330$.

8.3.2 Secondary Task Performance

The 3D IC version shows advantages over its 2D counterpart for the secondary tasks. Figure 8.6 and 8.7 illustrate the descriptive statistics of the measures for unexpected and expected events. Regarding the measures for the expected events, the participants judge the positions of the symbols more accurately using a 3D representation analyzing the mean, $F(1,54) = 21.503$, $p < .001$, $\eta^2 = .29$ and standard deviation, $F(1,54) = 11.740$, $p < .001$, $\eta^2 = .18$, of the distances between symbol and target zone. Analyzing the information complexity we found no significant effect for neither the mean, $F(1,54) = 1.240$, $p = .270$,

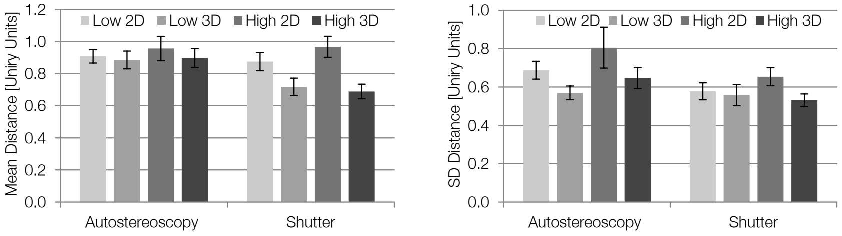

Figure 8.6: Means and standard errors as error bars for the secondary task measures regarding expected events. The mean (left diagram) as well as the standard deviation (right diagram) of the distance between symbol and target zone shows that task performance improves for a stereoscopic visualization.

nor the standard deviation, $F(1,54) = 2.748$, $p = .103$, of the judgments. In addition, the used display technologies do not significantly influence the mean, $F(1,54) = 2.267$, $p = .138$, and standard deviation, $F(1,54) = 3.370$, $p = .072$. There are no significant interaction effects except for the interaction between visualization and technology regarding the mean distance between symbol and target zone, $F(1,54) = 10.031$, $p < .003$, $\eta^2 = .18$. Figure 8.6 depicts that the S3D effect does not improve depth judgment for the autostereoscopy but for the shutter sample.

Comparing 2D against 3D, there is a significant difference for TCT when reacting on unexpected instructions to the advantage of 3D, $F(1,54) = 7.726$, $p = .007$, $\eta^2 = .13$. Neither the used display technologies, $F(1,54) = .160$, $p = .691$, nor the degrees of information complexity, $F(1,54) = .204$, $p = .653$, show significant effects for the measurement of TCT. We found no interaction effects for TCT, $p > .404$. In general, the participants reacted very accurately on

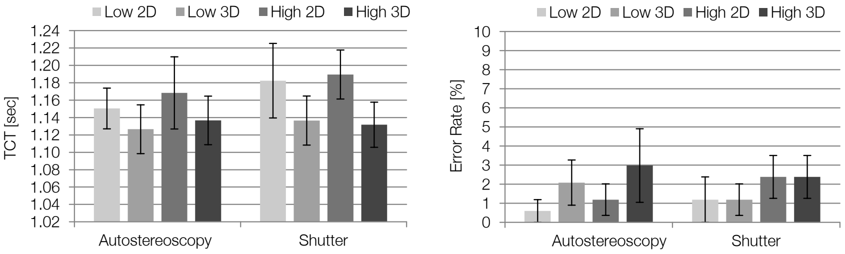

Figure 8.7: Means and standard errors for the TCT and error rate for reacting on unexpected events.

the unexpected instructions. Since the data of the error rates are not normally distributed, we used a Mann-Whitney test for analyzing the main effect on the used technology and separately analyzed the two samples (autostereoscopy and shutter) with Friedman ANOVAs. We found no significant differences for the display technology, $U = 421.000$, $p = .568$, as well as for the four within conditions of the autostereoscopic, $X^2(3) = 1.320$, $p = .724$, and the shutter sample, $X^2(3) = 2.455$, $p = .484$.

8.3.3 Gaze Behavior

For analyzing the gaze behavior, we measured the mean glance duration and the total number of glances onto the IC for the autostereoscopic sample. Figure 8.8 shows that the mean glance duration increases for the stereoscopic conditions as well as for higher information densities. In contrast, the total number of glances is quite similar for the four conditions. In fact, the influence of the 3D visualization is not statistically significant for both measures the mean glance duration, $F(1,27) = 3.691$, $p = .065$, and the total number of glances, $F(1,54) = .856$, $p = .363$. But there is a statistically significant effect of the different levels of information complexity for the mean glance duration onto the IC, $F(1,27) = 9.645$, $p = .004$, $\eta^2 = .263$, to the benefit of the low information level. Analyzing the total number of glances does not show a significant effect for the information complexity, $F(1,27) = .198$, $p = .660$. Furthermore, we did not find a significant interaction effect for the mean glance duration, $F(1,27) = .318$, $p = .577$, and the total number of glances, $F(1,27) = .528$, $p = .474$.

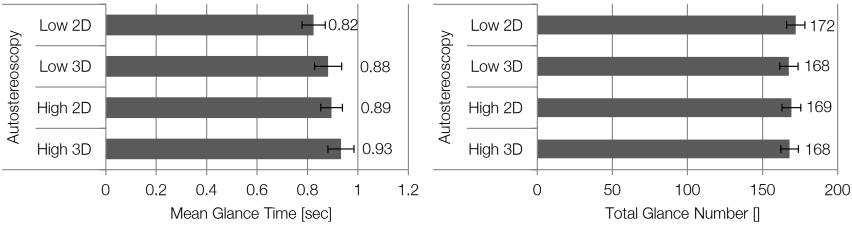

Figure 8.8: Means and standard errors for the mean glance duration and the total number of glances onto the IC for the autostereoscopic sample.

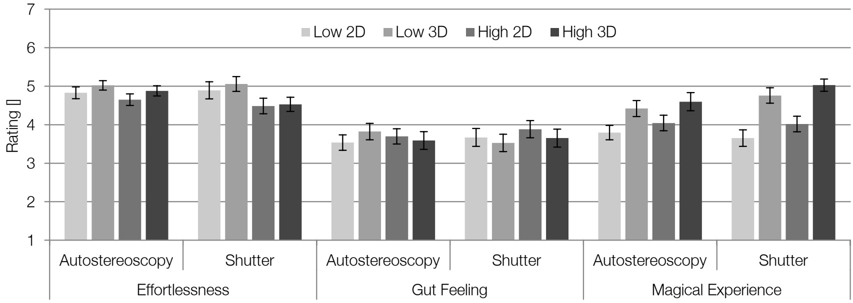

Figure 8.9: Means and standard errors for the rating of the selected dimensions of the INTUI.

8.3.4 Subjective Measures

As subjective measures we used the INTUI, DALI, and SSQ. Figure 8.9 shows the results of the INTUI for the three measured dimensions. *Effortlessness* is statistically significant for information complexity to the benefit of the low complexity level, $F(1,54) = 15.296$, $p < .001$, $\eta^2 = .22$, but not for the tested visualization levels, $F(1,54) = 3.536$, $p = .065$, and the used display technologies, $F(1,54) = .251$, $p = .618$. There are no significant interaction effects, $p > .061$. Except the interaction of Visualization * Complexity, $F(1,54) = 4.103$, $p = .048$, $\eta^2 = .07$, *Gut Feeling* does not reveal any significances for the tested variables, $p > .117$. In contrast, *Magical Experience* shows significant effects due to the visualization, $F(1,54) = 65.236$, $p < .001$ $\eta^2 = .55$, the information complexity, $F(1,54) = 5.618$, $p = .021$, $\eta^2 = .09$, and the interaction of Visualization * Technology, $F(1,54) = 5.282$, $p = .025$, $\eta^2 = .09$. Figure 8.9 illustrates that 3D is superior to 2D and that the high information density gains advantage over the low information degree for this dimension. Moreover, the 3D effect of the shutter technology provides larger scores than autostereoscopy.

Figure 8.10 shows the descriptive statistics for the total scores of the DALI and the SSQ. The DALI reveals statistically significant decreased ratings for the 2D visualization of the IC, $F(1,54) = 7.795$, $p = .007$, $\eta^2 = .13$. However, the results show no statistically significant differences due to the display technology, $F(1,54) = .147$, $p = .703$, and the information load, $F(1,54) = 1.205$, $p = .277$. Moreover, there are no significant interaction effects, $p > .283$.

Figure 8.10 shows that the total scores of the SSQ are very small (<15) compared to the maximum possible score of 235.62. An ANOVA shows that there are no sig-

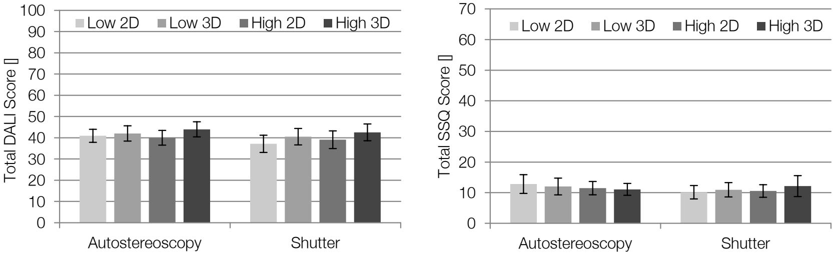

Figure 8.10: Means and standard errors for the total scores of the DALI and the SSQ.

nificant differences for the visualization, $F(1,54) = .081$, $p = .777$, information complexity, $F(1,54) = .024$, $p = .877$, and display technology, $F(1,54) = .082$, $p = .776$. All tested interactions are not significant, $p > .372$. Beside the total score, we also analyzed the three dimension of the SSQ (i.e., nausea, oculomotor, and disorientation) and could not find any significant effect.

Analyzing the rankings, the shutter sample clearly ranked the 3D conditions better than the 2D conditions (Low 3D: $Mdn = 1.5$; High 3D: $Mdn = 2$; Low 2D: $Mdn = 3$; High 2D: $Mdn = 4$). In regard to the autostereoscopic sample, the preference tends just slightly towards 3D (Low 3D: $Mdn = 2$; High 3D: $Mdn = 2.5$; Low 2D: $Mdn = 3$; High 2D: $Mdn = 3$). We tested the rankings for each group (shutter and autostereoscopy) separately. A Friedman test does not reveal statistically significant differences of the four conditions for the autostereoscopic sample, $X^2(3) = 4.929$, $p = .177$, but for the shutter sample, $X^2(3) = 33.347$, $p < .001$. Pairwise Wilcoxon tests with Bonferroni corrections show that the participants rated all 3D conditions significantly better than the 2D conditions (cf., Table 8.2).

Table 8.2: Test statistics of the pairwise Wilcoxon tests analyzing the rankings of the shutter sample.

	Low 2D vs. High 2D	Low 3D vs. High 3D	Low 2D vs. Low 3D	High 2D vs. High 3D	Low 2D vs. High 3D	High 2D vs. Low 3D
Z	-1.117	-.735	-4.072	-3.948	-2.762	-4.054
p	.264	.462	**> 0.001**	**> 0.001**	**0.006**	**> 0.001**

8.4 Discussion

The conducted driving simulator study reveals several insights into the influence of visualization, technology, and complexity when introducing 3D displays to automotive UIs. In the following, we discuss the findings based on the results and the qualitative feedback from the participants (P1–P56). We refer to our hypothesizes defined in Section 8.2.

8.4.1 Influence of S3D Visualization

According to H1-PT we expected an influence on the primary task. However, the findings from our study yield no influence of an S3D visualization on the primary driving task. We assume that two contradicting effects may have superimposed each other and, hence, obscure a potential main effect. On the one hand, our log data shows that S3D increases the user's secondary task performance, which in turn allows more attention to be directed towards the primary driving task. Participants feel supported in filtering the relevant information due to the 3D effect. They state that the spatial arrangement of the items "clarifies priorities" (n = 9), "fosters the display's structure" (n = 9), and provides an "intuitive understanding of spatial relations" (n = 18). On the other hand, 3D artifacts and the AC mismatches can induce eye strain, dizziness, or headache that can negatively affect the primary driving task. But the results of the SSQ do not show a significant effect on the drivers' condition. Based on the multiple resource theory of Wickens [251] the spatial-visual characteristics of presenting information with a 3D display can interfere with the spatial-visual task of driving. Indeed, participants subjectively rate S3D as more distracting than 2D. The participants' comments justify the perceived distraction through the "fascinating" (n = 4) character of S3D and increased visual load (n = 6). Our gaze data do not show statistical significances but a tendency towards increased visual load due to S3D. Nevertheless, we can not accept H1-PT and H1-G as our results do not show a significant influence of S3D on primary task performance as well as gaze behavior.

With regard to the secondary driving task we hypothesize an increase in user performance. In accordance, our study shows that the 3D visualization supports depth judgments and accelerates reactions on pop-out instructions. The shutter sample reveals an average decrease of 53 ms when an unexpected event is highlighted by binocular disparity. This means, the breaking distance can be reduced by 1.4 m driving with a speed of 100 km/h. Former research already showed that binocular highlighting can decrease visual search times [102] and TCTs [4, 230]. In consequence, we can accept H1-STJ and H1-STH.

Furthermore, S3D has a positive influence on attractiveness, user experience, and acceptance. Participants state the 3D effect to be “creative” (n = 2), “stylish” (P6), “cool” (n = 3), “modern” (n = 5), “attractive”, (n = 5), “fascinating and innovative” (n = 6). This conforms to prior findings (cf., Section 5.3) and to former comparisons of 2D and 3D presentations for gaming [206], automotive [22], and mobile applications [228]. Therefore, we regard the hypothesis H1-UX as confirmed.

8.4.2 Influence of Visual Complexity

Regarding the level of information complexity we expected a negative influence on UX (H2-UX), gaze behavior (H2-G), as well as primary (H2-PT) and secondary task performance (H2-ST). In accordance, the degree of information complexity has a significant effect on the primary driving task in terms of longitudinal control, which allows us to accept hypothesis H2-PT. Moreover, a reduced visual complexity decreases eyes-off-the-road time and results in better subjective ratings of effortlessness. This allows us to accept hypothesis H2-G. As the information complexity does not show any significant impact on the measures of the secondary task performance, we have to reject the hypotheses H2-ST. Nevertheless, the participants mentioned the 3D effect to “declutter” (n = 4) and as an “improve in clarity” (n = 8) for the visualized information, “particularly for high information densities” (n = 3). Based on our data, the improve in user experience as well as secondary task performance due to 3D holds true for low as well as high information complexities.

Although our study shows that higher information complexities reduce performance and increase driver distraction, participants perceived the IC with the higher information load as more attractive. We assume that the increased information densities foster the drivers’ confidence and provide a feeling of control. As a consequence, we reject hypothesis H2-UX.

8.4.3 Influence of Display Technology

As our results show, the use of autostereoscopy has a positive impact on the primary driving task. The decrease in driving performance for shutter is attributable to the flickering and the decrease in brightness while wearing the active glasses. In addition, participants state that the glasses are “annoying” (n = 8). Certainly, automotive UIs require autostereoscopic technologies. Yet, autostereoscopic technologies lack in 3D quality which comes to the cost of potential advantages due to the 3D effect.

As expected in hypothesis H3-ST, the shutter technology increases secondary task performance in terms of the accuracy in making depth judgments compared to the autostereoscopic display. This result corresponds to the findings of Alpaslan et al. [3] showing better task performances for shutter compared to autostereoscopic displays. We assume that the decreased accuracy of judging depth is a result of the low quality of the applied autostereoscopic display as well as the reduced depth budget in order to lower stereoscopic artifacts like crosstalk. Particularly tasks that require the perception of higher parallaxes are affected as it is the case for the depth judgment task. A second reason is the reduced resolution of the autostereoscopic technology that probably affects the accuracy in judging depth.

Finally, the display technology has a significant influence on user experience and user acceptance. Again, the superior 3D quality of the shutter technology due to the higher display resolution and the absence of crosstalk leads to better subjective ratings for the attractiveness and the preference of the 3D effect.

8.4.4 Limitations

We acknowledge the following limitations of the presented study. First, the perceived brightness of the display is not consistent across conditions because of the darkening factor of the shutter glasses. Moreover, we had to reduce the parallax budget for the autostereoscopic display to provide comfortable 3D images. Both are confounding factors that could have an influence on user performance. Second, we conducted our study in a driving simulator. While this increases internal validity (e.g., we are able to control the traffic), it reduces the external validity. However, we deliberately opted for this setting, as we needed a highly controllable environment for an initial evaluation while not putting participants at risk by driving on a real motorway. Third, the proposed (secondary) tasks are artificial. Even though these tasks would not be performed in real world driving scenarios they are quite similar to tasks like responding to routing instructions, navigation cues, or urgent alerts as warnings and notifications. We believe that the chosen tasks allow for transferring the results to various use cases of automotive UIs.

8.5 Summary

In this chapter, we investigated the influence of S3D on the user's primary and secondary task performance as well as on cognitive and visual load in an automotive setting. We developed an interactive 3D IC with two levels of complexity. We conducted a driving simulator study to evaluate the impact of a stereoscopic visualization, the used 3D display technology, and the level of complexity on the driver. The core findings of our study provide designers of future S3D UIs specific hints how to optimally support the driver:

Clarify Spatial Relations of UI Elements with Binocular Disparity: Users perform better in secondary tasks using 3D visualizations. Since the drivers judge spatial relations between UI objects more accurately, S3D can enhance UI elements which represent distances, for examples to a preceding car or of navigation cues.

Use Stereoscopy to Highlight Urgent Information: Highlighting single instructions using S3D shortens interaction times. Hence, using S3D is advisable to highlight urgent content (e.g., warnings and notifications).

Choose an Appropriate Display Technology: Autostereoscopic displays are more suited for automotive UIs, since glasses are disturbing and reduce the primary task performance. However, the quality of the 3D effect is crucial for secondary task performance. Thus, we suggest that autostereoscopic displays should exhibit a 3D quality comparable to state-of-the-art shutter technology for a successful integration into cars.

Consider the Complexity of the Displayed Content: Higher information complexities reduce primary task performance and increase distraction. At the same time, they make UIs more attractive. Structuring information on different depth layers using S3D can reduce the perceived complexity by decluttering the content.

Despite the limitations of our study, the outcomes reveal that S3D interfaces offer attractive benefits compared to their 2D counterparts. Nevertheless, users judge the 3D effect distracting due to its fascinating character. We believe that the chosen secondary tasks let us transfer the results to various automotive use cases (e.g., ACC, navigation, warnings, notifications, etc.). As a next step, we plan to increase the external validity by implementing real automotive use cases to verify this translation.

Finally, designing S3D UIs is in many ways challenging particularly with regard to the safety-critical automotive context that requires the user to engage in concurrent tasks. The findings of this research support the development of reasonable S3D UIs and point towards aspects that influence their successful application in cars (e.g., the used display technology).

Chapter 9

Manual Driving in the Real World

In the last chapter, we identified several benefits of using stereoscopic visualizations while manual driving. We used a driving simulator setup in order to maximize internal validity. In this chapter, we aim at validating the applicability of 3D displays in cars in a real-world driving scenario. Especially for automotive UIs, this is an important step since driving through a virtual environment can have a significant influence on the driver's behavior (e.g., driving mistakes do not have serious consequences) and consequently reduces the ecological validity [190]. We assume that interacting with a 3D display while maneuvering the car through a real 3D world can significantly impact the user's perception of the system in terms of usability as well as user experience. Particularly, the forces that affect the driver due to the acceleration can result in an increase of possible discomfort associated with stereoscopic content. Moreover, glances while driving in a real environment are shorter as in the simulator [243] due to the increased risk awareness. This requires the visual system to quickly identify the required information. The effort for the eyes can increase to correctly perceive the S3D effect and, hence, hampers the readability of the UI. Last but not least, the natural 3D perception of the real world can interfere with the artificial depth perception of the stereoscopic display. As a result the 3D effect can impair the orientation in the real 3D environment as well as the perception of the stereoscopic content provided by the in-car display.

In this chapter, we present our test vehicle which we equipped with an autostereoscopic display as instrument cluster (IC). We report on two real-world driving studies using this prototype and investigating the difference between a S3D UI and its 2D counterpart. First, we conducted a study in an urban environment with 15 experts in automotive UI design providing their expert opinion about the in-car use of 3D displays. Second, we ran a real-world evaluation with non-experts. Based on the expert feedback, we deliberately investigated the use of S3D for encoding urgency in this second real-world study. Finally, the development of the test vehicle, as well as the planning and the execution of both real-world studies allowed us to establish simple principles for evaluating novel UI technologies in real-world environments.

This chapter is based on the following publications:

- N. Broy, S. Schneegass, M. Guo, F. Alt, and A. Schmidt. Evaluating Stereoscopic 3D for Automotive User Interfaces in a Real-World Driving Study. In *Proceedings of the Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, CHI EA ’15, New York, NY, USA, 2015. ACM
- N. Broy, M. Guo, S. Schneegass, B. Pfleging, and F. Alt. Introducing Novel Technologies in the Car – Conducting a Real-World Study to Test 3D Dashboards. In *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI ’15, New York, NY, USA, 2015. ACM

9.1 Related Work

In general, secondary task performance can decrease for real-world evaluations [193] since the driver is more focused on the driving task due to their increased risk awareness [61, 190]. However, driving simulator studies are more sensitive to identify effects of secondary tasks on driving performance compared to on road investigations [14, 188]. Hence, the increased costs and effort of real-world studies due to the considerably higher safety requirements are not appropriate for early investigations of in-vehicle devices [190, 202]. Although high-fidelity driving simulators have a close to 360° view and provide kinesthetic feedback, a driving simulation can not fully replicate real-world environments, also regarding

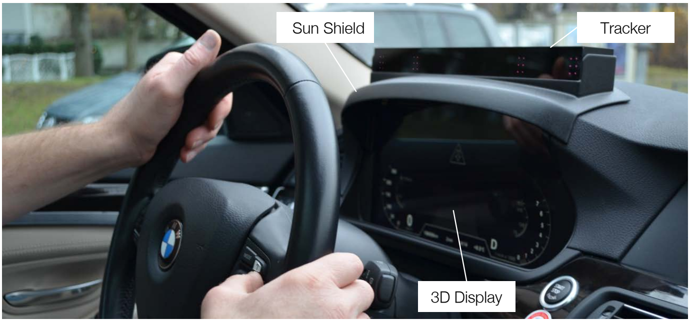

Figure 9.1: We replaced the IC of a car with an autostereoscopic display technology using eye tracking to adjust the sweet spot.

the induced workload, risk tolerance, and realism. When the development of in-vehicle devices has reached a certain level, the real-world validation of effects initially found in a driving simulator is necessary to fully understand parameters of novel interfaces [190, 202].

In fact, research on stereoscopic displays in the car is very young. To our knowledge investigations existing so far were conducted in the laboratory [22,230] or in the simulator [182]. These studies prove potentials of using S3D compared to monoscopic representations rather than showing a negative impact on driver distraction. As a result, we deliberately opt to validate and extend former findings in the real world.

9.2 Test Vehicle

In order to explore the effects of a 3D display in real-world environments, we replaced the IC of a BMW 5 series with a 13.3" autostereoscopic display using a native resolution of 1920 x 1080 pixels (pixel pitch: 0.153 mm). The used display provides a significantly better 3D quality compared to the autostereoscopic solution we applied for the simulator study (cf., Chapter 8). The car has a automatic transmission that considerably facilitates the driving task. Furthermore, it is equipped with a HUD and a CID. These displays ensure the correct representation of relevant information, for example speed and check controls, in the case of a malfunction of the embedded hard- and software of our stereoscopic IC prototype. The vehicle is equipped with ACC and a multifunctional steering wheel.

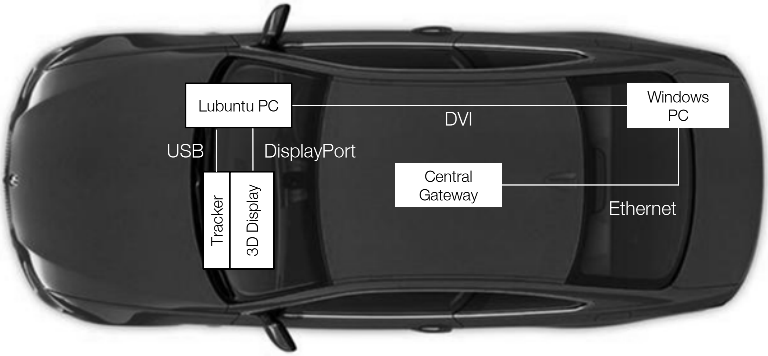

Figure 9.2: The test vehicle is equipped with several components to supply a stereoscopic display as IC.

We applied an autostereoscopic display technology developed by SeeFront GmbH[38] providing a reasonable 3D quality. It consists of a display unit, an eye tracker, and a Lubuntu PC. The display uses lenticular lenses to create the S3D effect. On top of the display unit an eye tracker is located. It enhances the 3D effect by adjusting the sweet spot in accordance with the viewer's eye positions. We positioned the display in a way that the tracker can detect the viewer by tracking the area above the steering wheel (cf., Figure 9.1). The viewing distance from driver to the display can vary between 60 and 90 cm. A 3D printed sun shield integrates the display and tracking unit into the car's interior. Please refer to the Appendix VI for more information on the placement of the display.

A Windows PC from CarTFT[39] is mounted in the trunk. It creates the simulation of the IC and passes a side-by-side image via DVI to the display. The Lubuntu PC interlaces the left and right image in regard to the tracker data. We placed the Lubuntu PC in the footwell of the front passenger side. The Windows PC is connected via Ethernet with the central gateway of the car. In this way, the IC application receives real-time vehicle data such as speed and rpm, etc. We used Unity[40] with C# as scripting language to build the interactive IC application. For the studies, we logged the data at a frequency of 60 Hz. Figure 9.2 depicts the arrangement of the integrated components in the vehicle.

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[38] http://www.seefront.com, last accessed July 17, 2015.

[39] http://www.cartft.com, last accessed July 17, 2015.

[40] https://unity3d.com/, last accessed October 19, 2015.

Figure 9.3: Side view of the IC showing the depth layout of the UI elements as parallaxes in pixels.

9.3 Expert Review

For an initial evaluation of the prototype, we conducted a real-world driving study with experts in the domain of automotive UIs. We focused on the assessment of qualitative feedback about the usefulness of in-car 3D displays but also considered quantitative data. We based our study on an heuristic evaluation approach to gather highly reliable and insightful opinions on a S3D IC. The experts conducted two drives, one with a monoscopic (2D) and one with the S3D version of the IC in counterbalanced order. In the following, we present the UI of the IC as well as the conducted real-world study. The results point to promising directions for future investigations.

9.3.1 User Interface

We arranged typical elements of an automotive IC in 3D space following the principles presented in Part III. We used positive parallaxes up to 35.7 arc-min and negative parallaxes up to 9.8 arc-min. Figure 9.3 depicts the spatial distribution of the objects. Please refer to Appendix VII for the S3D visualization of the developed IC. In the following, we shortly describe its UI elements.

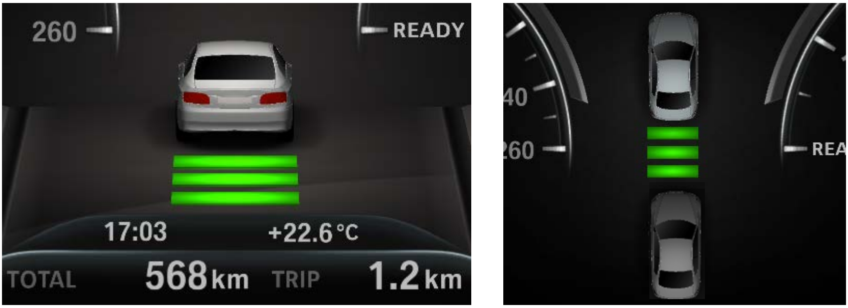

Figure 9.4: Perspective view and bird's-eye view of the ACC.

Gauges

Two large gauges for rpm and speed are located slightly behind the screen. The speedometer and the rpm gauge emphasize their current value by highlighting the corresponding number of the scale via depth, its luminance, and its size in order to maximize readability. Beside the big gauges there are two small ones displaying the fuel level and the oil temperature. In general, this information is less relevant than speed and rpm. Therefore, these gauges are located behind the layer of the speed and rpm gauge.

Abstract Driving Space

In the middle of the display, an abstract visualization of the road is visible which reaches from the screen to the rearmost plane. The 3D space it offers can be used to visualize systems that comprise distance information as ACC. If the driver activates ACC, green bars on the street represent the distance that the car maintains to a preceding vehicle. A 3D car model located behind the green bars indicate if the system detects a vehicle ahead. Beside this perspective view, we implemented an alternative visualization depicting the ACC status in a bird's-eye view (cf., Figure 9.4). The ACC speed and distance can be adjusted by using buttons on the steering wheel. Beside the ACC visualization, the abstract representation of the street can be used to encode spatial and timely relations of upcoming events, for example, navigation cues.

Status Information

At the origin of the abstract street, status information (trip, outside temperature, etc.) is placed at screen depth.

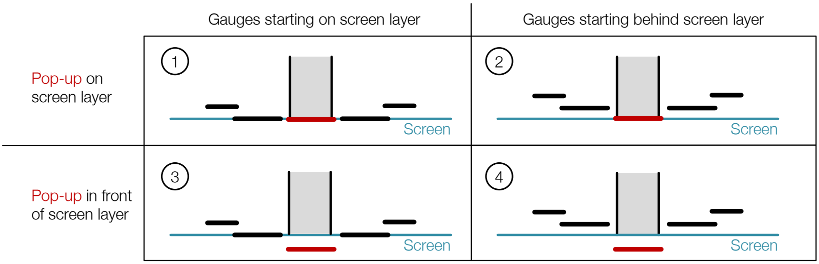

Figure 9.5: We implemented four depth layout alternatives. In the study, the experts drove with variant 4.

Check Controls

Since control lights have a warning character they are placed on screen depth to visually separate them from the gauges. The x and y positions are chosen in accordance with their location in the serial IC of the BMW 5 series.

Notifications

The foremost layer in front of the screen plane is used for urgent information. We integrate three types of notifications that can be triggered by the experimenter and be displayed as pop-ups in front of the screen or as an integral part of the UI.

- **Navigation Cues:** The cues announce navigation instructions in the form of an arrow, street name, and distance in meters, appearing 400 m before an intersection. While pop-ups appear and stay in front of the screen layer (decreasing the distance value in meters in discrete steps as the car approaches the intersection), the visualization inside the UI appears at the rearmost depth layer and moves in concrete steps towards the screen plane, thus, encoding the actual distance to the maneuver.

- **Speed Limit:** The speed limit info (SLI) notifies the driver about a new speed limit by means of a speed limit sign. The UI visualization shows the upcoming SLI shortly before reaching it. As the navigation cues, the upcoming SLI sign starts at a rearmost depth layer and moves towards the screen layer encoding its distance to the vehicle.

- **Low Fuel Level:** The pop-up visualization shows a gas station symbol and the text “Fuel Level Low". The variant inside the UI highlights the fuel gauge by moving it towards the screen layer and flashing it.

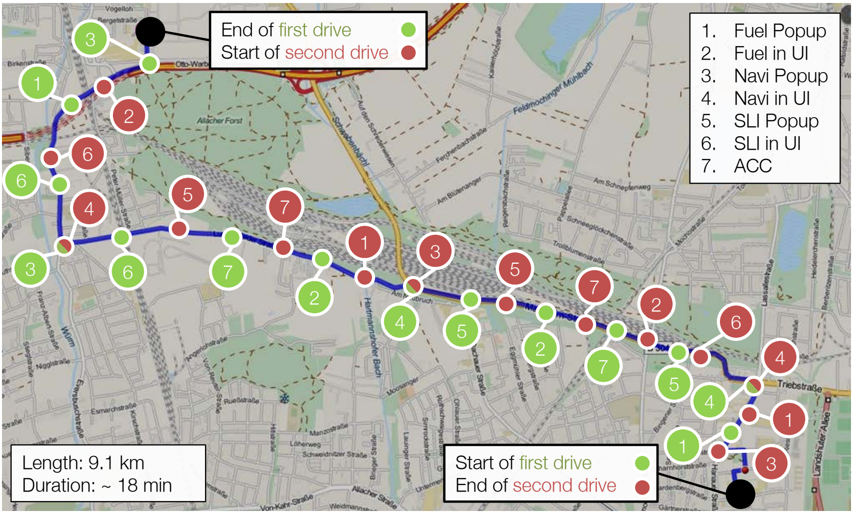

Figure 9.6: The task order is adapted to the characteristics of the route. It slightly differs between the first and second drive.

All pop-up visualizations of the different content types have a similar visual layout and are displayed in front of the screen layer. In addition to the presented depth layout, we could vary the depth position of the gauges and the pop-up as depicted in Figure 9.5. While driving all participants used the depth layout variant 4 and the perspective view of the ACC.

9.3.2 Study Design, Tasks, and Route

The study started and ended at the participants' place of work. Since our participants were located at two different places we applied two different routes which just slightly differed in the first and last kilometer. Each route is divided in two drives, one for each display mode (2D and S3D). Each drive had a length of 9 km and took roughly 20 minutes. The participants were instructed to observe the traffic rules and to follow the navigation cues visualized in the IC.

As secondary tasks, participants had to react to notifications in the IC by pressing a button on the steering wheel as soon they recognized the notification and its content. As a result, the participants frequently checked the IC for upcoming events. The presented notifications differed in three within variables:

- **Visualization:** We presented the participants a monoscopic (*2D*) and a stereoscopic (*3D*) visualization of the IC.
- **Content:** The notification are of three content types: *Navigation*, *SLI*, and *Fuel* level. We applied rather noncritical content instead of warnings (e.g., collision warning) in order to avoid critical driving reactions (e.g., braking).
- **Integration:** The notifications are visualized either as elements integrated into the *UI* or as *pop-ups*.

Each participant had to react twice to the $2 \times 3 \times 2 = 12$ notification conditions. We counterbalanced the order of the IC visualization (i.e., 2D, 3D). The participants also drove short distances with ACC (perspective view). Note, that for safety reasons we focused on tasks causing minimal distraction and that users were familiar with from everyday driving. The task order (notifications and ACC) was adjusted to the characteristics of the route (cf., Figure 9.6).

As quantitative measures, we used the task completion time (TCT) for pressing the steering wheel button due to a notification. Moreover, we measured the mean gaze duration on the IC using a glasses-based eye-tracker produced by the company Pupil Labs[41]. After each drive, the participants filled in a mini AttrakDiff [89] and DALI questionnaire [178]. Using the 3D mode, the participants rated their preference pertaining the alternative visualizations of the ACC (i.e., birds' eye vs. perspective view) and the four depth layout variants of the IC from one (best) to four (worst). As qualitative measures we conducted semi-structured interviews. We based the interviews on principles of automotive UI design. Hence, we asked closed and open-ended questions about the general impression of the UI (2D/3D preference, potentials and drawbacks of S3D), readability and gaze behavior, depth layout, and the presented functions (e.g., ACC, navi cues). Please refer to the Appendix VIII for the protocol of the study procedure which also describes the conducted interviews.

9.3.3 Procedure

As participants arrived, we showed them the respective visualization (2D/3D) of the IC for their first drive and all notifications used during the study. We instructed them to press a button on the steering wheel once they recognized a notification. Moreover, we encouraged participants to think aloud during the test

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[41] http://pupil-labs.com/, last accessed July 17, 2015

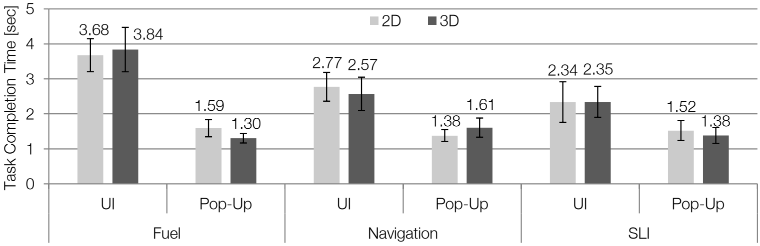

Figure 9.7: Means and standard errors as error bars for the TCT of confirming the notifications.

drive to express their impressions and feelings. Most importantly, we told the participants to focus on the driving task at any time and ignore tasks if they felt uncomfortable to attend to these.

After participants adjusted seat, mirror, and steering wheel they began driving. The first drive ended in a large parking lot where we handed out the mini AttrakDiff and DALI. After completing the questionnaires, we interviewed the participants about their experience. Then we started the second drive with the other visualization mode – again followed by questionnaires and an interview concerning the last drive and the comparison between driving with a 2D and S3D IC. Finally, the participants ranked the four different depth layout modes (cf., Figure 9.5) and the two visualizations of the ACC in S3D (cf., Figure 9.4). Each test session took about 90 minutes and was videotaped using two GoPro cameras.

9.3.4 Results

We recruited 15 participants (6 female, 9 male) aged between 28 and 43 years ($M = 32.6$, $SD = 4.48$). All of them were employees at the BMW Group and work on automotive UIs in the research or development department. Their backgrounds covered the fields of computer science, engineering, design, and psychology.

Quantitative Results

Task Completion Time: We analyzed the TCT for recognizing the notifications regarding the three independent variables (visualization, content, integration). Due to technical issues in logging the button presses, we had to exclude 3 participants for analyzing the TCT. Figure 9.7 shows that the TCT are very similar

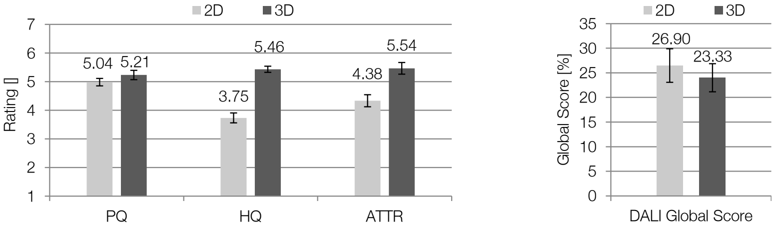

Figure 9.8: Means and standard errors as error bars for the AttrakDiff (left) and the global score of the DALI questionnaire (right).

for the 2D and 3D variants of the IC while the TCT considerably decreases for pop-up elements compared to the elements integrated in the UI. A three-way repeated measures ANOVA shows significant main effects for the three content types, $F(2,22) = 4.073$, $p = .031$, $\eta^2 = .270$, and the two integration levels, $F(1,11) = 30.164$, $p<.001$, $\eta^2 = .733$. There are no significant differences between the two visualization variants, $F(1,11) = .031$, $p=.864$. The ANOVA reveals a significant interaction effect between content and integration, $F(2,22)=3.499$, $p=.048$, $\eta^2 = .241$, showing that in the UI integration of the fuel notification is recognized slower than the integrated variants for navigation and SLI. All other interactions do not show statistical significances, $p > .612$.

Gaze Data: The tracker often did not recognize the used markers (printed on paper) due to very bright light conditions. As a result, we could just use the data of eight participants. Even for these eight the markers were not recognized for every single task. Hence, we aggregated the available data by the two visualizations. It shows that the mean gaze duration on the IC is slightly higher for the 3D ($M = .565$ ms, $SD = .224$) than the 2D ($M = .556$ ms, $SD = .288$) version.

AttrakDiff: The left diagram of Figure 9.8 depicts the descriptive statistics for the AttrakDiff. It shows that 3D outperforms 2D for the three dimensions of the AttrakDiff (i.e., PQ, HQ, and ATTR). However, the differences are not statistically significant for PQ, $T(14) = -1.662, p = .119$, but for HQ, $T(14) = -7.218$, $p < .001$, and ATTR, $T(14) = -5,724$, $p < .001$.

DALI: The right diagram of Figure 9.8 shows that the mean DALI score is lower for the 3D than the 2D drive. A t-test reveals that the effect is not significant, $T(14) = 0.947, p = .360$.

Rankings: Regarding the rankings of the favored depth layout, variant 1 ($MD = 3.33$, $SD = 1.23$) was ranked worst while the other variants, 2 ($MD = 2.20$, $SD = .86$), 3 ($MD = 2.07$, $SD = .45$), and 4 ($MD = 2.27$, $SD = 1.34$) were ranked quite similar. Note, that lower values indicate better rankings. A Friedman ANOVA shows that the differences are statistically significant, $X^2(3) = 8.554, p = 0.036$. Regarding the two alternative visualizations of the ACC, 12 participants favored the perspective visualization and three the bird's-eye visualization. A Wilcoxon test shows that the preference of the perspective version is statistically significant, $Z = -2.324$, $p < .020$.

Qualitative Results

For presenting the qualitative results from the interviews and discussions with the experts (referred as P1–P15) we clustered the statements regarding different categories. Furthermore, we tagged if they were positive/negative towards the 3D/2D representation. We also analyzed opinions about the visualization of the presented functions (i.e., notifications, ACC).

General Impression: The acceptance of novel technologies is crucial for the market of new products. Beside usability aspects, attractiveness and aesthetics play a major role. We explicitly asked the participants which version of the tool they prefer. Fourteen out of 15 participants favored the 3D version of the UI. The participant favoring 2D stated to have strong interocular differences, causing problems to perceive the 3D effect. This is in line with prior findings of Goodwin and Romano [73]. They showed that significant interocular differences have a negative influence on stereo vision. Because of the problems in the depth perception the respective participant perceived the 3D effect as unnecessary and preferred the 2D version. The other experts explain their preference for 3D as it appears more “natural” than 2D (n = 4) and entails an “innovative” character (n = 4). In addition, participants rated the 2D version as “boring” (n = 4) and “ordinary” (n = 7). In contrast, one participant (P1) emphasized the “familiarity” and “simplicity” of 2D. Looking at usability aspects, all participants emphasized the usefulness of the spatiality that 3D offers to clarify relations between UI objects and to facilitate the estimation of distances. Moreover, six participants explicitly stated that 3D declutters the display. Although nobody felt discomfort or visual fatigue, five experts mentioned possible discomfort as disadvantage of S3D, particularly in combination with long term use. Five experts warned not to use the 3D effect too excessively and three explicitly mentioned that the 3D space can confuse the user. As a result, users may need to develop new search strategies, since more than one depth layer has to be scanned. They propose to use depth in a subtle way and just for those elements that obviously benefit from S3D. Moreover, two persons are uncertain about the best locations in depth for the UI elements since design aspects possibly provide contradicting depth preferences than aspects that concern information processing and attention.

Regarding the display technology, 12 experts mentioned issues pertaining an automotive application, such as the high reflections of the display (n = 4), the performance of the tracker (n = 5), the display's contrast (P4), and the reduced resolution (P1, P5). Five participants were positively surprised by the quality of the used autostereoscopic technology.

Readability: In total 12 participants positively mentioned the readability of the S3D IC, but only four rated it better in 3D and seven in 2D. Mentioned reasons for the reduced readability in 3D are of technical nature. Reflections are perceived more prominent in 3D than 2D and the tracker sometimes induces jitter for S3D presentations.

Gaze Behavior: Altogether seven participants felt to look more frequently and also longer at the IC in the 3D version. However, some of them attributed this to the novelty of this display type (n = 5). Other arguments comprise that perceiving the information in 3D requires an "increased level of concentration" (P11, P12) and that processing information is quicker in 2D (P1). Six participants perceived no difference in their gaze behavior between 2D and 3D. However, four participants considered the 3D effect to positively influence their gaze strategy, since "it declutters the display" (P5, P7, P12) and "is more comfortable to look at" (P15). We explicitly asked the participants to comment on the attention switch between display and driving scene. Thirteen participants had no problems with switching between the 3D IC and the real world at all. Four participants even stated that switching was easier with 3D since it "appears more natural" (P3), "does not confront the user with one cluttered plane" (P4), and allows "faster" (P1) and "more effortless" (P15) switches. However, two participants (P10, P12) stated that they need longer gaze durations to perceive the 3D effect while nine participants noted that the 3D effect is instantly visible.

Depth Layout: All participants recognized that more important and urgent objects are placed further to the front. They welcomed the use of S3D to structure information on layers since it increases the "clearness of the display" (P7, P9), "declutters" (n = 6), "improves the usability" (P13), "comprehensibility" (P3), "comfort and mode awareness" (P12), and "facilitates the separation of objects" (P9, P15). Particularly, the depth layout of the gauges is "suitable" (n = 3) and "appealing because of the symmetric depth layout" (P7, P15). In addition, four participants suggested to "use S3D for evoking a sportive mood". A major challenge is the distribution of the check controls on the screen layer. While following a well-known arrangement in 2D, these controls seem to be "lost in space" (n = 6) in 3D. A "better integration in the 3D UI is required" (P5), for example "by additional grouping in the x and y dimension" (P3, P14). Moreover, three experts were confused by the depth position of the pointers belonging to the big gauges since those are located behind the dial. They considered this arrangement as “unintuitive” (P4, P5) since “it dissents from expectation towards familiar analogue gauges” (P13). In addition, three participants criticize that “the gauges themselves involve to many depth layers” and desired the gauges to be “flatter”. In general, 11 participants appreciated the use of S3D for highlighting objects (pop-ups) since it expresses “urgency” (n = 4) and “currentness” (P2, P6). Using this semantic, P8 proposed to visualize several urgency levels via S3D with the pop-out effect being the ultimate escalation level. The other four participants did not cherish highlighting with S3D since depth positions in front of the display are “difficult to perceive” (P15) and other cues, such as size and color are “sufficient” (P7) and more “suitable” (P9, P10).

Functions: The participants experienced ACC as well as different notification strategies for the navigation, SLI, and fuel level. For the chosen types of content, the pop-up visualization was considered as “too obtrusive” due to its “urgent and warning character” (n = 8). Regarding the fuel notification in the UI, seven participants did not notice that the fuel gauge steps slightly forward. Five participants liked the depth movement of the in-UI fuel gauge, since it is a “comfortable” and “ambient” solution that “corresponds” to its urgency level. However, two participants rated this effect as critical as it is contradicting and unexpected that “physical objects” move to the front (P3, P15). All participants saw great potential in S3D for visualizing temporal and spatial relations, as demonstrated by the perspective view of the ACC and the in-UI visualizations of SLI and navigation cues. Using depth as a metaphor for the distance to upcoming signs or navigation maneuvers is “supportive” (n = 5) and “clarifying” (n = 7). This is also reflected by the fact that four experts did not understand the movement of SLI and navigation cues in 2D but all for the 3D vision mode. As improvement some participants suggested to animate the notifications continuously instead of discrete steps. Concerning ACC, participants felt that S3D increases the comprehensibility of “spatial relations between objects” (n = 5) and the “analogy to the driving scene” (n = 4). In general, eight persons desired a more perspective distortion for the ACC. Four explicitly mentioned this as improvement for the 3D visualization and six for the 2D version. As a general improvement, some participants suggested to enhance the abstract street by integrating more elements of the real driving scene such as prominent buildings and traffic signs (P8, P15).

9.3.5 Discussion

One main finding of this study is that using S3D while driving is not rated as hazardous or demanding but beneficial. The experts did not mention severe problems in perceiving the displayed content and switching the gaze between real and virtual 3D world except for technology problems such as jitter induced by the tracker. Nevertheless, some experts felt that the 3D visualization requires slightly longer eyes-off-the-road times in order to assess the targeted information. This is in line with the tendencies of the gaze data gathered in this study as well as in the simulator. Further research needs to clarify gaze strategies used in 3D compared to 2D visualizations. Moreover, some experts consider visual discomfort as a result of long term use.

The qualitative feedback of the expert users identifies the clear visual communication of spatial relations as the main potential of S3D UIs. Hence, using S3D is particularly useful for use cases such as navigation and ACC. The experts emphasized that S3D visualizations have a strong benefit to improve the comprehensibility of such UI elements. Furthermore, a well-considered depth layout of these elements helps to declutter the displayed content. At the same time, interface designers need to take care that depth positions correspond to user expectations and that the S3D effect is applied reasonably to avoid spatial clutter and discomfort. Our study shows that even while driving through the real world a reasonable S3D effect does not evoke discomfort or was rated as distracting. Additionally, S3D can be used to increase the perceived urgency of UI elements although we could not find decreased TCTs. Finally, S3D strongly improves the hedonic quality of the UI while driving. It offers a new dimension for designing the UI, for example, to stage moods as sportiness. In general, this study validates potentials found in the simulator. This demonstrates that the 3D effect is well accepted by the experts though display technology needs to improve for commercial use.

9.4 Encoding Urgency

In a further real-world study, we evaluate the 3D effect with non-experts. Therefore, we apply an improved version of the IC UI based on the expert feedback collected in the previous section. In particular, we are interested in the use of stereoscopy for encoding urgency. Color plays a major role to encode the significance of information. Red is the color reserved for danger messages [36] and

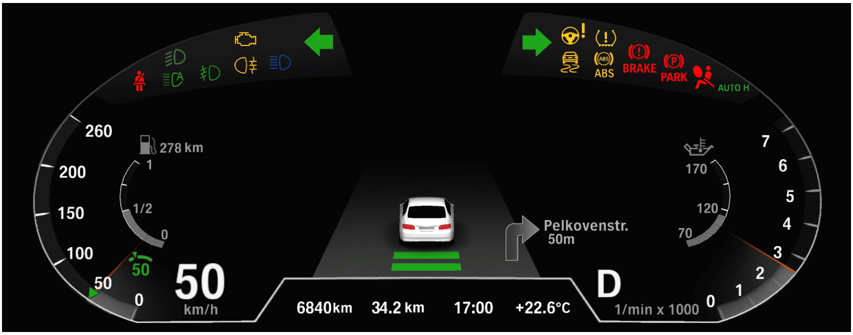

Figure 9.9: The IC places speed, rpm, check controls, and status information at the outer edge to clear space for elements which can profit from a 3D representation as, for example, Active Cruise Control.

is well associated with risk [136]. Nevertheless, the salience of visual warnings need to be maximized in order to attract attention in the competition with various visual stimuli [259]. Former research showed that the combination of color and stereoscopic depth improves search times [162] as well as TCT for graph analysis tasks [4]. Moreover, participants of the expert study also suggested to encode the level of urgency along the depth plane. We conducted a real-world study with 32 participants that have to rate the urgency of visual cues presented on one of three different depth levels in either white or red color. We gathered feedback about the acceptance of a stereoscopic visualization of informative content while driving. Our results show that color has a greater impact on the perceived urgency than stereoscopy while their combination maximizes urgency ratings. Moreover, this study validates a strong increase of user experience due to a S3D visualization and the gain of UI elements that present temporal and spatial relations.

9.4.1 User Interface

We used the expert feedback of the previous section to improve the visual layout of the IC. Thus, we applied abstract scales instead of resembling analogue gauges and cleared more space for spatial elements such as ACC. In addition, we used rather simple 3D shapes to avoid spatial clutter and greater perspective distortions. The developed stereoscopic IC optimally exploits 3D space by applying the shape of a tunnel ranging from screen depth to the rearmost depth plane. The current speed as well as rpm are displayed on a scale at the outer edge of the IC tunnel at screen depth (cf., Figure 9.9). The scales for the fuel level and the oil temperature are aligned inside the tunnel behind the speed and rpm scales in order to encode their lower priority. At the bottom of the tunnel status information is displayed on screen depth. Check controls are located on two dedicated panels on top of the IC tunnel. In this way, we provide a visual anchor for those elements avoiding their perception as lost in space as some experts noted. The place between the two panels is dedicated to notifications, instructions, and warnings, that are displayed on various depth levels and colors in accordance with their level of urgency. We deliberately placed the check controls as well as urgent information at the top of the IC in order to minimize the distance to the driver's line of sight. All these elements are placed at outer locations of the IC. This clears space for the flexible presentation of spatial information inside the IC tunnel, as navigation cues and ACC, a 3D map, as well as a 3D navigation menu for entertainment functions. We implemented three content elements between the driver can toggle using a steering wheel button. The *abstract driving space* displays the same content (ACC, SLI, Navigation cues) as the IC used for the expert study. A *3D map* visualizes a 3D representation of the current driving scene in order to enhance navigation tasks. Furthermore, there is a small *infotainment menu* that allows the driver to choose between various audio sources. The menu displays two lists on two different depth planes. A steering wheel button allows switching between the two lists while the currently selected list is placed further to the front. The driver can scroll through the selected list and select items using steering wheel buttons. The three available content elements (i.e., abstract driving space, map, menu) are visualized by icons on a turntable which appears when toggling between them. It turns clockwise as well as the three content elements in order to visualize a reasonable appearance and disappearance of the elements in 3D space. Please refer to Appendix VII for a S3D visualization of the IC.

9.4.2 Hypotheses

One key finding of several studies about stereoscopic presentation is the increase of attractiveness of the shown content [22, 81, 206]. Nevertheless, even if stereoscopy offers a pleasant experience it induces simulator sickness symptoms [83, 206]. This issue was also mentioned by some experts in the previous study. Moreover, the processing of the stereoscopic content can increase visual and cognitive workload and in turn decreases the performance in the driver's reaction. Stereoscopy is a salient cue. In conjunction with other salient cues, as for example color and motion, Nakayama and Silverman prove that visual search times do not increase with an increasing number of distractors [162]. Alper et al. [4] show that highlighting nodes in graphs using stereoscopy and color significantly improves user performance for tasks commonly used for the analysis of graph data. In addition to the findings of related work, the outcomes of the simulator study (cf., Chapter 8) as well as the qualitative feedback of the experts (cf., Section 9.3) let us derive four hypotheses:

- H1: The driver rates the user experience and the attractiveness of the IC higher when interacting with a S3D visualization.
- H2: Cognitive workload increases when the IC is visualized in S3D.
- H3: Simulator sickness symptoms increase when the driver uses a S3D IC.
- H4: The urgency of content elements is rated higher when they are positioned closer to the user in 3D space.

9.4.3 Study Design, Tasks, and Route

For the evaluation of the stated hypothesis, we conducted a real-world driving study with non-experts. We used the same route as for the expert review. The route consisted of two drives, one for driving with a monoscopic representation and one for a stereoscopic visualization of the IC. In contrast to the expert review, all participants exactly drove the same route starting and ending at the same location. Their primary task was to safely maneuver the car observing the traffic rules. While driving, the participants used the IC view of the abstract driving space and had to follow the navigation cues.

As secondary tasks, we instructed the participants to react on instructions placed between the two check control panels. The instructions displayed a triangle with an arrow pointing up- or downwards. Once the participant noticed the instruction, they had to react by pressing the toggle button on the right side of the steering wheel up- or downwards. This task corresponds to the unexpected events which we used in the driving simulator study in Chapter 8.2. If the participant correctly reacted by pressing the toggle button in the displayed direction, the arrow inside the triangle switched to a star icon. This visualization of the instruction rests for three more seconds on the screen. Directly after the reaction on the instruction, the participants intuitively rated the urgency of the visualization using a four-point Likert scale (1 = not urgent at all; 4 = very urgent). We used rather abstract content for this task (arrows and stars) in order to avoid any influence on the perceived urgency due to the displayed content. While the participants reacted on the instructions they did not use ACC. Nevertheless, they experienced driving

ACC for two short segments of each drive. Overall, we varied three independent variables using a repeated measured design:

- **Visualization:** We presented participants a monoscopic (*2D*) and a stereoscopic (*3D*) visualization of the IC.
- **Depth Layer:** The instructions appearing in the IC were displayed either in front of the screen (-14 pixels parallax), on screen level (0 parallax), or behind the screen (14 pixels parallax). We applied these parallaxes of the instructions regardless of the visualization mode. Hence, the 2D visualization depicted the instructions stereoscopically while all other IC elements were visualized monoscopically. Note, that the displayed elements maintain their size on the screen for all three depth positions.
- **Color:** The instructions were either colored in *white* or *red*.

We counterbalanced the presentation of the visualizations over all participants. For each visualization level the participants had to react on all $3 \times 2 = 6$ task conditions four times (twice on arrows pointing upwards and twice on arrows pointing downwards). This results in 24 instruction tasks per drive which were presented in random order. The tasks were triggered by the experimenter in order to display the instructions in driving situations that are comparable and allow for the interaction with the display. All tasks (navigation, ACC, instructions) did not apply any auditory cues in order to investigate visual cues without the interaction of other modalities.

We measured TCTs as well as error rates and the urgency rating on a four-point Likert scale for reacting on the instructions. We did not apply gaze measures as a remote eye tracker interfered with the tracker of the used autostereoscopic display. Moreover, during the expert study we observed that the used glasses-based tracker decreased the performance of the display's detection of the user's eye positions which is responsible for adjusting the sweet spot of the 3D display. As technological shortcomings could significantly decrease both usability and user experience, we deliberately opted to drop this measure in order to maximize the performance of the used autostereoscopic technology. After each test drive the participants filled in a mini AttrakDiff, a SSQ, as well as a DALI questionnaire and rated statements about their gaze behavior and the information structure of the display on a five-point Likert scale (1: strongly disagree; 5: strongly agree). At the end of the study, we interviewed the participants about the test drives and the visualization modes of the IC in general, its abstract driving space, map, and list view.

9.4.4 Procedure

We met the participants in front of the workshop of BMW Research and Technology at the test vehicle. First, the participants adjusted the seat, mirrors, and the steering wheel in order to optimally operate all driving controls and to get the best view on the IC. After the participants get to know some basics of S3D we tested their ability to view stereoscopic content with a RDS test (cf., Appendix II) and color blindness using a Ishihara color test. If participants passed both tests they qualified for the study and filled in a demographic questionnaire and baseline SSQ. Then, the examiner showed and explained the IC and its components in the respective vision mode (2D/3D) of the first drive as well as the navigation, ACC, and the instruction tasks. The participants were instructed to primarily focus on the driving task and to observe traffic rules but to react on displayed instructions accurately and fast if the traffic situation allows for it.

Before driving, the participants practiced 12 instruction tasks in order to get acquainted with first using the steering wheel button and then to tell their urgency rating. After the participants felt comfortable with the tasks, they practiced the navigation and instruction tasks while driving a short test track around the block before the first test drive started. Then the two test drives started, one in 2D and one in 3D. After each test drive the participants filled in the questionnaires. They were instructed to rate the interaction with the IC with no regard for technical issues of the display (e.g., low resolution) and the rather artificial instruction tasks. Before driving with the second vision mode the participants explored the IC and its components once again. At the end of the study, we conducted a semi-structured interview with the participants about the IC and its S3D visualization.

9.4.5 Participants

We recruited 32 participants (5 female, 27 male) aged between 22 and 51 years ($M = 34.63$, $SD = 7.96$) through our internal mailing list. All participants were employees of the BMW Group and have already received special driver training that allows them to steer test vehicles in public. In contrast to the expert review, the participants were not experts in UI development and covered rather technical backgrounds ranging from mechanics over electrical and mechanical engineering to computer science. Three participants had no experience in viewing 3D content at all, while the remaining 29 participants knew stereoscopy from cinema and games (e.g., Oculus Rift). Eight participants reported problems encountered with 3D displays as ghosting, blurred images, headache, dizziness, and nausea.

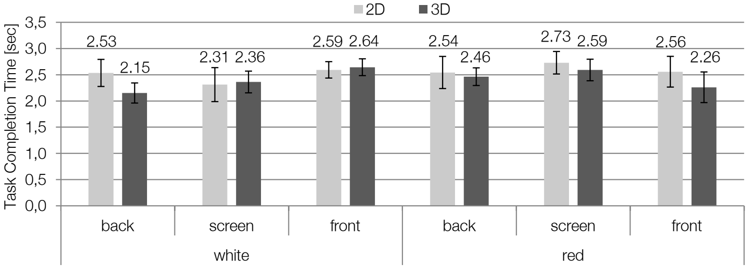

Figure 9.10: Means and standard errors as error bars for the TCT of confirming the instructions.

9.4.6 Results

In the following, we report the results of the study for the measures recorded while driving (TCT, error rate, urgency rating), the applied questionnaires, and the qualitative feedback of the participants.

Secondary Task Performance

Based on the three independent variables, visualization, depth layer, and color, we analyzed the TCT and error rates for reacting on the instructions. Figure 9.10, depicting the descriptive statistics for the TCT, does not reveal a specific trend for the tested conditions. A three-way ANOVA does not show significant different TCTs for the tested visualizations, $F(1,31) = .678$, $p = .417$, depth layers, $F(2,62) = .307$, $p = .737$, and colors, $F(1,31) = .543$, $p = .470$. Moreover, all interactions of the tested factors are not significant, $p > .102$.

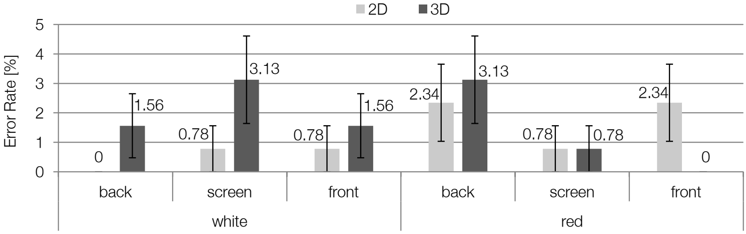

Figure 9.11: Means and standard errors as error bars for the error rates of confirming the instructions.

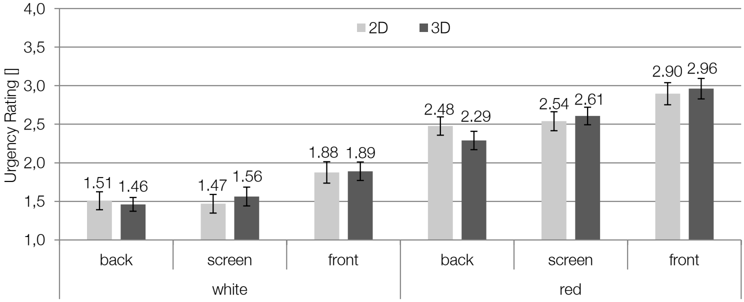

Figure 9.12: Means and standard errors as error bars for the urgency rating of the instructions.

In general, the participants reacted correctly on the instructions. Over all presented tasks in the test conditions the participants made less than 1.436 % errors. Figure 9.11 depicts the small error rates. Since the data of the error rates is not normally distributed, we aggregated the data by each independent variable and analyzed these data sets with nonparametric tests. Wilcoxon tests do not reveal significant results for the visualization, $Z = -1.155$, $p = .248$, as well as the color, $Z = -.484$, $p = .629$. Moreover, a Friedman test does not show statistically significant differences for the applied depth layers, $X^2 = .041$, $p = .980$.

Perceived Urgency

After reacting on the instructions the participants intuitively rated on a four-point Likert scale the perceived urgency which they attribute to its presentation. Figure 9.12 shows that the rating increases for the red colored icons and for instructions with negative parallaxes while the visualization does not impact the rating. Please note, that the 2D mode applies the exact same parallaxes for the instructions as the 3D mode and just depicts the remaining GUI elements without binocular disparity. A three-way ANOVA is statistically significant for color, $F(1,31) = 67.873$, $p < .001$, $\eta^2 = .686$, and the different depth layers, $F(2,62) = 16.884$, $p < .001$, $\eta^2 = .353$. The visualization has not a significant influence, $F(1,31) = .001$, $p < .972$. Moreover, we found significant interaction effects for visualization * depth layer, $F(2,62) = 6.436$, $p = .003$, $\eta^2 = .172$, and color * depth layer, $F(2,62) = 3.706$, $p = .030$, $\eta^2 = .107$. The interactions visualization * color, $F(1,31) = .667$, $p = .420$, and visualization * depth layer * color, $F(2,62) = 2.172$, $p = .122$, are not statistically significant.

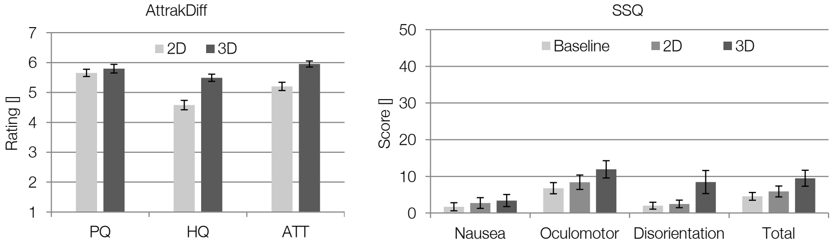

Figure 9.13: Means and standard errors as error bars for the dimensions of the AttrakDiff (left diagram) and the SSQ (right diagram).

Questionnaires

After each drive the participants filled in several questionnaires.

AttrakDiff: Figure 9.13 shows that the 3D version of the IC increases all dimensions (HQ, PQ, ATTR) of the AttrakDiff. Paired sample t-tests prove that these differences are significant for HQ, $T(31) = -5.015$, $p < .001$, $r = .448$ and ATTR, $T(31) = -4.425$, $p < .001$, $r = .387$, but not for PQ, $T(31) = -.944$, $p = .352$.

SSQ: The participants filled in the SSQ questionnaire before the study started serving as baseline and after each of the two test drives. Figure 9.13 shows that the scores of each dimension (Nausea, Oculomotor, Disorientation) and the total score are in general very low[42]. Values are lowest for the baseline measurement. The 3D variant of the IC has a negative impact on all dimensions and the total score compared to its 2D counterpart. Since the data is not normally distributed we used nonparametric tests for a statistical analysis. Friedman tests show that the differences between the measures are not significant for nausea, $X^2(2) = 5.375$, $p = .068$, oculomotor, $X^2(2) = 3.309$, $p = .191$, and the total score $X^2(2) = 5.233$, $p = .073$. In contrast, testing the dimension disorientation reveals statistical significances, $X^2(2) = 7.154$, $p = .028$. However, pairwise comparisons using Wilcoxon Tests with a Bonferroni corrected alpha level ($\alpha = .017$) do not reveal significant results for comparing the baseline with 3D, $Z = -2.226$, $p = .026$, the baseline with 2D, $Z = -.447$, $p = .655$, and 2D with 3D $Z = -2.047$, $p = .041$.

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[42] The maximum total score is 235.62

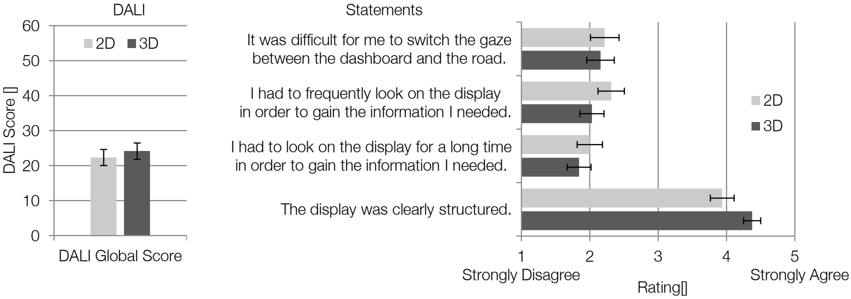

Figure 9.14: Means and standard errors as error bars for the global score of the DALI (left diagram) and the rated statements (right diagram).

DALI: The global DALI score is slightly increased for the 3D IC compared to its 2D variant, as Figure 9.14 shows. However, this tendency is not statistically significant, $T(31) = 2.239$, $p = .302$.

Statements about Gaze Behavior and Information Structure: Figure 9.14 shows that the statements about gaze behavior are in favor of the 3D version. However, Wilcoxon tests show that there are no statistical differences between the 2D and 3D IC version for the ratings about switching the gaze, Z=$-$.599, p=.549, the gaze duration, Z=$-$1.574, p=.116, as well as the gaze frequency, Z=$-$1.048, p=.295. Nevertheless, 3D significantly increases the rating for the statement about the clarity of the displays structure, Z=$-$2.810, p=.005, r=.497.

Qualitative Feedback

In the following, we report on the qualitative feedback of the participants and refer to them as P1–P32.

General Impressions: 28 of all 32 participants would rather use an S3D IC, while two (P15, P32) chose the 2D representation and two (P17, P27) could not make an explicit decision. Reasons for the 2D variant are that it is “faster” (P32) and “easier” (P15) to read and that it provides a clearer functional overview (P15, P27). Nevertheless, most comments on the IC are to the benefit for the S3D version. It is commented as more “attractive” in an aesthetic way (n = 11), “innovative” (n = 4), “natural” (P20, P25), “high quality” (P11, P22), “creative” (P20, P25), and provides more “impressive features” (n = 9). In contrast, the 2D IC representation appeared “usual” (n = 4) and rather “boring” (P2, P25). Two participants commented that the difference between the two visualizations is rather small. P17 stated that S3D only contributes to particular elements. Some participants reported problems with reading from the S3D IC version with four persons complaining about longer focus times to perceive elements in S3D and three participants rating S3D presentations as cumbersome to read. As disturbing factor some participants mentioned the "dynamic behavior" of the S3D presentation (n = 5) due to "motion parallax" (n = 4) and tracking problems which induce jitter (n = 3). As we did not implement motion parallax, the dynamic appearance arises due to shear distortions, which are a typical artifacts of stereosopic displays [260].

ACC: All participants welcomed the S3D effect for the ACC representation. In particular, the S3D visualization of the ACC was commented as attractive (n = 12), realistic (n = 8), and interesting (n = 4). However, six people emphasized that the S3D effect does not improve the functionality of the ACC.

Navigation Cues: In contrast to ACC, the participants pointed out the functional use of S3D for depicting navigation cues and less mentioned the aesthetic value for this use case. Although the participants correctly followed the navigation instructions in all conditions, they commented that the S3D visualization greatly enhanced the relation to the real world and contributed to the recognition of the turning point (n = 12). In general, 31 participants preferred S3D for the navigation cues while one participant (P19) did not notice much difference.

3D Map: In total, 31 participants preferred the 3D version of the map. One participant (P15) claimed that it takes more time to focus on the 3D map and thus preferred the 2D version. Fifteen participants attributed it as a "cool" and "attractive" feature. The S3D effect fits well for the map visualization (P3, P24) as it improves the perspective and spatial perception (n = 4).

Infotainment Menu: With regard to the infotainment list, the S3D version was favored by 24 participants. Seven persons prefered the 2D list because it "requires less effort for focusing" (n = 4), "is more familiar", "simpler" (n = 3), and "better readable" (n = 3). Positive aspects attributed to the S3D list are a better focus on where the interaction takes place (n = 8) and improved item segregation (n = 8).

Information structuring: 28 participants stated to have immediately perceived the depth structure of the S3D IC. We explained the depth layout for those who did not instantly recognize the S3D structure. After clarification, 30 of 32 participants said that the information structure is suitable. 21 participants acknowledged the use of depth to encode the importance of information. Moreover, structuring the information by means of depth layers decluttered the display (n = 6). Nevertheless, one participant (P15) rejected the use of S3D for structuring information and recommended to use color and contrast instead.

9.4.7 Discussion

In the following, we discuss the results and hypotheses of this real-world experiment with regard to prior findings. In general, we obtained similar findings compared to previous simulator studies. Our results validate a significant increase of user experience and attractiveness due to the S3D visualization which is consistent through lab (cf., Section 5.3) and simulator studies (cf., Chapter 8). Thus, our data allows us to accept hypothesis H1.

The DALI does not show a significant difference between the 2D and 3D representation of the IC. Moreover, participants felt that the S3D visualization does not have a significant influence on their gaze behavior. The findings regarding the gaze behavior as well as the primary driving task performance are in line with the former simulator study (cf., Chapter 8). However, the simulator study revealed a significant increase of the DALI due to a S3D visualization. Our investigation in the real world could not verify this finding. The simulator study of Pitts et al. [182] showed that a stereoscopic visualization can decrease eyes-off-the-road times. Note, that they applied a rather artificial task which benefits from a stereoscopic visualization. However, during the interviews some participants noted a decreased readability of 3D content. Further research needs to clarify if this decrease is a result of the used display technology or the S3D effect itself. We can not accept hypothesis H2.

In contrast to the former simulator study (cf., Chapter 8), S3D shows a negative influence on SSQ ratings. Hence, we accept hypothesis H3. Nevertheless, it is unclear which roles the used parallax settings as well as the used autostereoscopic display including the tracker performance play. Participants noted motion parallax to have a negative influence. Since the perceived motion parallax is a result of shear distortion, this stereoscopic artifact needs to be compensated [260]. As this finding is not a result of any laboratory or simulator study, we claim that the dynamic motions resulting from driving through the real world are the reason for detecting this issue.

Although our prior simulator study (cf., Chapter 8) as well as other lab and simulator studies [182, 230] demonstrated a significant increase in secondary task performance due to stereoscopy, our results show no difference in TCT or error rate for the instruction tasks for all tested variables (i.e., visualization, color, depth layer). We claim that the uncontrolled real-world situation hampers the sensitivity for identifying this effect. Nevertheless, the applied rating shows that the used depth layer as well as the color have a significant influence on the perceived urgency of the instructions. Thereby the color has a greater effect than the used depth layers. Nevertheless, positioning content in front of the screen significantly increases the perceived urgency. Hence, we can accept hypothesis H4.

The qualitative feedback of the participants yields an interesting insight on the navigation task. While participants emphasized the increased attractiveness of ACC due to S3D, their comments focused on the functional use of the navigation cues in S3D. One of the strengths of the S3D presentation is that it strongly matches to the real 3D environment. Since a simulator study can not reproduce the matching of a real 3D world with an artificial S3D interface this result is solely verifiable in a real-world environment.

Qualitative feedback reveals that S3D strongly enhances the usability of the infotainment list. Depth highlighting the focus of interaction makes the interaction easier for the participants. This is in line with findings from a former lab study about a S3D infotainment menu [22]. In general, participants rated that S3D contributes to clarifying the IC structure.

9.5 Real-World Study Approach

During the planning and execution of both real-world studies, we took several precautions to maximize safety for all participants. In the following, we summarize key aspects of our approach which allowed us to gather data of high ecological validity.

Real-World Studies for Validation: The driving simulator is highly sensitive in identifying effects of secondary tasks on driver performance without putting the participants at risk. If new technologies reveal promising findings in simulator studies without a negative impact on driver distraction, these technologies qualify for a validation in the real world. We claim that prior investigations in the lab as well as in the simulator are necessary before planing a study in the real world. We deliberately based our investigation on former studies conducted in the lab and the simulator.

Reduce Task Complexity: Driving simulator environments allow for a safe evaluation of secondary tasks, even if inducing high cognitive workload. There are approaches that also integrate a tertiary task such as a peripheral detection task to measure workload. Since these tasks represent a further source of distraction, we neglected those methods for our investigations on real roads. We based the real-world study about urgency on simple reaction tasks. We have already used this task in the former simulator study in combination with a depth judgment task (cf., Chapter 8). We dropped the additional depth judgment task for the real-world investigation to decrease the complexity of the secondary tasks. It is also advisable to minimize the complexity of the driving task by choosing an appropriate route excluding difficult junctions and dense traffic as well as using a car with automatic transmission.

Provide backup for primary task relevant information: Evaluating systems that carry important driving information such as, for example, speed and warnings, need to be fully reliable. If this is not the case due to a prototypical implementation, there need to be systems that reliably communicate this information. In our case, we used a test vehicle equipped with a HUD that shows important information as a fallback in the case of any errors.

Provide in-depth instructions: Participants were extensively acquainted with the system and the study before starting the engine. In this way, participants got used to the new technology and the tasks. The participants practiced the tasks together with the urgency rating as long as they felt comfortable with this procedure. After that, they practiced the tasks once more while driving in a low traffic and at a low speed (30 km/h). As all participants had no problems in solving the tasks during the study this procedure optimally prepared the participants.

Manually trigger tasks: During the study one experimenter accompanied the participant. The experimenter took the seat of the co-passenger to optimally monitor the traffic situation. In this way, the experimenter could alert and support the driver in critical traffic situations. Moreover, the experimenter triggered the secondary tasks so that at no time safety-critical situations occurred.

9.6 Summary

In this chapter, we presented an expert and user evaluation in the real world of using an autostereoscopic display as IC. The outcomes validate prior findings of lab and simulator studies, namely that S3D increases the user experience, clarifies the information structure of the display, and does not significantly affect driver workload. We found that S3D slightly increases discomfort in comparison to a 2D display. Moreover, we deliberately investigated the use of S3D to encode urgency. Our results show that color has a greater impact on communicating urgency than S3D, while the combination of both maximizes the perceived urgency. Moreover, the presented real-world investigations provide detailed insights on the use of S3D in cars which are hard to find in the simulator. Although shear distortions are a disturbing factor and need to be eliminated, S3D allows for an easy translation between the real and virtual 3D world.

Furthermore, we presented our lessons learned on conducting real-world driving studies for evaluating novel UI technologies in the car. We suggest to use the real-world approach as a complementary validation method for exploring novel interaction technologies in cars. A necessary requirement is that prior laboratory evaluations ensure comparable or lower driver distraction compared to state of the art technologies. Moreover, it is essential to carefully choose the test track, the test vehicle, the secondary tasks, as well as the study procedure. The presented studies exemplary demonstrated a successful approach for collecting data of high ecological validity.

Finally, we demonstrated the potentials of S3D visualizations for a highly sophisticated application of an IC while manual driving. As a further step, we face the transition to automated driving by investigating the effects of interacting with S3D UIs in those driving scenarios.

Chapter 10

Highly Automated Driving

Automation plays an increasing role in our everyday life. From switching in telephone networks over automated processes in the industry to the steering and stabilization of ships and aircraft, there are various recent and emerging applications with minimal or reduced human intervention. Also the automotive domain faces a paradigm shift from manual to highly automated driving. During the last decades, an increasing number of driving assistance systems have been integrated in middle and high-class vehicles. The fast development of computer vision, car-to-x communication as well as sensor technology promises that cars can transport passengers highly automated in the near future. The concept of highly automated driving requires the car to fulfill the complete driving task by means of lateral and longitudinal control [67]. This means the car observes traffic (e.g., preceding cars), traffic rules such as speed limits, keeps the driving lane, and can manage lane change maneuvers. The driver does not need to monitor the system anymore and is “out of the loop" [60]. Thus, the driver can concentrate on other tasks not related to driving such as working, relaxing, reading a book, surfing the internet, or playing games. However, the system controlling the driving task can not reliably handle every situation, for example, if an unknown object or situation approaches. In this case, it has to alert the user to take over the driving task within a certain time span (i.e., take-over request (TOR)). This time span should allow the driver to get back into the loop meaning to get cognitively as well as physically in a state that allows for an adequate reaction on the traffic situation.

We assume that applications used while highly automated driving have a significant impact on the take-over behavior of the driver. Hence, the applications should be designed in a way that optimally prepares the driver for the driving task when it comes to a TOR. As an important design dimension we consider the analogy between the application and the driving task itself. The driving task incorporates the assessment of the situation (situation awareness), making a decision and performing an action, e.g., steering or braking, [59, 60]. A major role for situation awareness is the driver's representation of spatial and temporal relationship among all traffic participants. In particular, we assume that visualizing the spatial and temporal characteristics of the driving task in the non-driving related task can prepare the driver on the take-over process. In this chapter, we deliberately investigate the impact of spatial as well as temporal representations within the non-driving related task. As an example, we look into the use of games as we assume gaming as a potential activity while highly autonomous driving. We present the game *SpaceTetris* that allows to vary its spatial and temporal analogy in regard to the driving task. In a driving simulator study, 47 participants played *SpaceTetris* while highly automated driving before they were confronted with a TOR. We varied the game's analogy to the driving task to assess its impact on the take-over behavior of the driver. As game variants we investigated a 2D and 3D visualization, addressing the spatial aspect of the driving task. Moreover, the positions of the game objects are synchronized or not synchronized to the traffic participants, addressing the temporal aspect of the driving task. The 2D variant of *SpaceTetris* does not incorporate any depth cues while the 3D version applies beside monocular depth cues binocular disparity. We chose these extreme variants to investigate the effect of three-dimensionality in a first step. The results show that the 3D visualization increases the take-over quality compared to 2D. Based on our study, we discuss design implications for applications that will be used while driving highly automated.

10.1 Related Work

Vehicle automation clearly has beneficial aspects such as an increased comfort level for the driver and road safety [226]. However, as long as the automation system can not manage every traffic situation, the human driver is needed as a fallback level. This assumption refers to the SAE definition of level 3 automation [198]. Therefore, “driving safety increasingly depends on the combined performance of the human and automation" [155]. With drivers being out of the loop during highly automated driving, the transition phase back to manual driving can be highly critical [60]. During the last years, substantial research has been done to address these issues. Damböck et al. [46] investigated, what time budget is necessary to allow the driver a comfortable take-over and errorless maneuver. They compared three levels of time budget (i.e., 4 s, 6 s, and 8 s) and propose a time frame of at least six seconds to provide a confident and comfortable take-over maneuver. Gold et al. [69] compared the drivers' reaction times and maneuver quality with 5 s and 7 s time budget in a take-over scenario. They further put these results in relation to driver performance when driving manual. This approach allows them to define characteristics for an improved take-over quality. For example, they define high accelerations as a decrease in take-over quality. To support the driver during the take-over process, Lorenz et al. investigated two different AR concepts [142]. Their results show that the AR visualization does not impact on take-over times but considerably affects the take-over quality and the maneuver chosen by the driver. Finally, with the raising level of automation in cars research focuses on possible modifications of the driver's interface. Kerschbaum et al. [123] investigated the decoupling of the steering wheel during highly automated driving as a first step to allow the comfortable utilization of drivetime.

Beside Radlmayer et al. [185], former research addressed less the influence of the non-driving related task on the driver's take-over behavior. Related studies [69, 123, 142, 185] excessively used the Surrogate Reference Task (SuRT) [105] as non-driving related task for evaluating take-over scenarios. There are a few studies that used more realistic tasks which users might choose to spend their time during highly automated driving such as reading articles from a weekly news magazine [163] or playing *twenty questions* [154]. We argue that the used application and particularly its design has an impact on the take-over behavior. In the following, we investigate the use of S3D for a non-driving related task (i.e., a 3D game) and the impact of the S3D visualization on the driver's take-over behavior.

10.2 Driving Simulator Study

We conducted a driving simulator study with 47 participants to investigate the effect of S3D for a non-driving related task on a take-over scenario. Based on our hypotheses we developed a game which the participants played during highly automated driving. In the following, we describe our hypotheses, the used prototype, as well as the user study.

10.2.1 Hypothesis

In Section 3.2, we introduced the sequential task paradigm which particularly addresses highly automated driving. Following Salvucci et al. [201], switching between two tasks is facilitated if these are related to each other. As a result, we assume that the similarity between the non-driving related task and the driving task has an impact on the driver's take-over behavior. In general, the driving task requires the creation of situation awareness on the driving scenario to make a decision that results in a certain action [59, 60] pertaining longitudinal and lateral control [2]. According to Starter and Woods [203], the understanding of the temporal and spatial relations between the own car and all traffic participants is necessary for a proper situation awareness. In consequence, we hypothesize that an increased similarity in spatial and temporal aspects improves the take-over behavior when it comes to an immediate TOR. The use of a 3D visualization addresses the spatial aspect. The temporal aspect can be covered by a synchronization of the spatial positions of UI elements in accordance with the traffic participants. We assume that such an analogy between the non-driving related task and the driving scenery can optimally prepare the driver for the driving task when a TOR occurs.

- H1: The take-over quality improves when the non-driving related task exhibits a 3D layout similar to the driving scene.
- H2: The take-over quality improves when the positions of the UI elements in the non-driving related task are similar to the positions of the traffic participants in the current driving scene.

10.2.2 Prototype and Study Setup

Non-Driving Related Task: Space Tetris

To test our hypothesis, we developed a game that allows to modify its visual analogy in regard to the current driving scenery. The game has to meet the following requirements to generate comparable variants:

- **R1 Analogy to the driving scene:** In general, the game exhibits a visual layout that demonstrates a similarity to the driving scene.
- **R2 Spatial layout:** The game offers means to switch between a 2D and 3D view. The 3D view requires the player to take care of the whole available

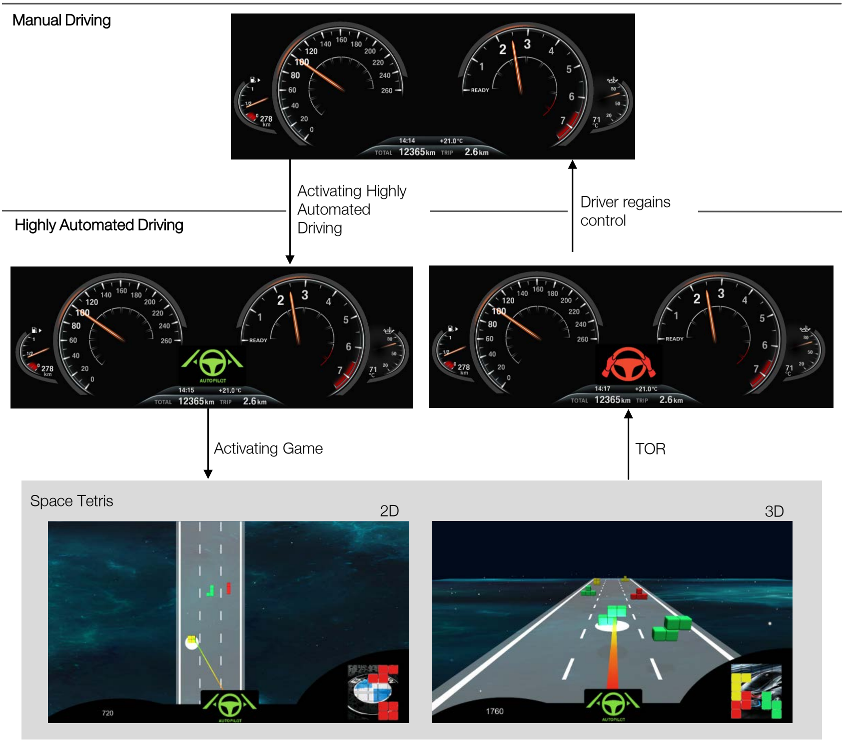

Figure 10.1: The instrument cluster (IC) allows to activate a game while highly automated driving. The game can be in 2D or 3D. If a TOR occurs the driver has to take-over the driving task.

3D space. In contrast, the 2D view deletes all available depth cues without changing game play and behavior. Note, that we investigate the effect of a spatial representation in general and not the particular application of stereoscopy.

- **R3 Interaction design:** Interacting with the game occurs via one single device allowing gaming with just one hand.

The main aim of *Space Tetris* is to collect *Tetris Tokens* in order to gain points and to unlock a *Trophy*. The game arena depicts a milky way in space, which is separated in three lanes (cf., R1). Figure 10.1 shows the game in its 2D and 3D view. The 2D view only differs from the 3D variant in its point of view to satisfy R2. Please refer to the Appendix IX for the S3D layout of the game. The *Tetris Tokens* move along the milky way and can be collected by a laser light which hovers over one of the three lanes. The player controls the laser with an iDrive controller, which is located in the center console (cf., R3). The rotary input device allows to rotate the top of the laser over the three lanes. If the top of the laser hits a *Tetris Token* it can be collected by pushing the controller. Than the player receives 10 points. For blinking tokens the player gets 100 points and gains a tile of the *Trophy* which is a picture displayed in the lower right. The application is implemented in Unity[43] using the script language C#.

Vehicle Mockup and Driving Simulator

We used a full vehicle mockup for the study. The vehicle mockup was placed in a dome which provides a projection with 220° field of view and kinesthetic feedback. The simulation also allows for using the side and rear-view mirrors. The vehicle is equipped with an autostereoscopic 3D screen as IC. The 3D display has a size of 13.3", a resolution of 1920x1080 and uses eye tracking for adjusting its sweet spot due to the viewer's position. The screen depicts the IC application running on an ASUS notebook G75VW. The notebook directly receives the signals of the iDrive controller via a CAN bus interface. Furthermore, the notebook is part of a private network enabling a two way communication between the application and the driving simulator via UDP. The application shows a typical layout of instruments. A button on the steering wheel allows the driver to activate highly automated driving which is shown by a green icon in the IC. In this state, the IC allows the user to start *Space Tetris*. The automation system of this experiment meets the requirements for highly automated driving defined by Gasser et al. [67]. Therefore, the driver has to reengage in the driving task within a certain time span when a TOR occurs. The system executes the longitudinal and lateral control of the vehicle and is able to overtake vehicles moving at lower than maximum permitted speed (120 km/h). We used a freeway with three lanes as test track. In the case of a TOR, a red icon flashes in the IC supported by an acoustic cue (sinusoidal tone "beep"). The TOR is triggered as soon as the automation reaches a system state, that can not handle the current situation, for example, an unknown obstacle or accident ahead. Figure 10.1 shows the states of the IC application. After a TOR the automation system keeps the current lane until the driver intervenes by steering or braking.

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[43] https://unity3d.com/, last accessed October 19, 2015.

10.2.3 Study Design

To keep the take-over scenarios comparable, we used for each test condition the exact same situation. The chosen take-over scenario is similar to scenarios used in related work [69, 123, 142, 185].

Take-Over Scenario

Figure 10.2 depicts the traffic scenery as the TOR occurred. The TOR was caused by a system boundary due to an accident on the right lane which is also the current driving lane. Two crashed cars stand on the right lane with flashing warning lights. The system triggered the TOR 233 meters (at 120 km/h) in front of the accident in order to provide a time budget of seven seconds. This time frame allowed the driver to make a proper decision in order to avoid a crash with the obstacle. The accident appeared simultaneously with the TOR to suddenly confront the driver with the obstacle. The participants could either perform an emergency stop on the right lane or swerve to the middle lane in order to avoid an accident. The middle lane was kept free from any other road user while two vehicles drove on the left lane (cf., Figure 10.2). Nevertheless, participants had to ensure a lane change by visually checking the corridor beside the car and using the mirrors.

Independent Variables

We used mixed study design with one between and one within independent variable:

- **Visualization (between):** As between variable we presented the game in a pure *2D* visualization for one sample and in *3D* for the other sample, addressing the spatial aspect of the driving task. We used a pure 2D visualization neglecting all depth cues and S3D visualization incorporating monocular as well as binocular cues to compare the extremes of spatiality.
- **Synchronization (within):** We specified two behaviors of the game 30 seconds before the TOR occurs. For the *sync* behavior the game arranged and moved the *Tetris Tokens* in exactly the same way as the traffic participants of the driving simulation (cf., Figure 10.2), addressing the temporal aspect of the driving task. The *async* behavior caused a defined procedure of the *Tetris Tokens*, but not in accordance to the traffic of the simulation. Keeping comparable synchronization levels we used the same amount of *Tetris Tokens* for both conditions.

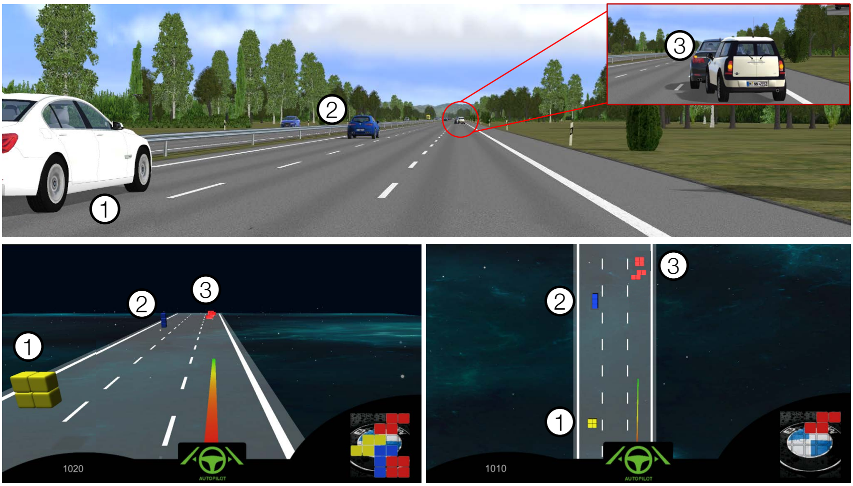


Figure 10.2: The position of the game objects were either synchronized or not synchronized to the traffic situation. The picture at the top depicts the take-over situation. The lower middle and right picture of the game depict the synchronized 2D and 3D variant. The numbers refer the traffic participants and the respective game objects.

We counterbalanced the sequence of the two synchronization levels (sync; async) over the samples for each level of the between variable (i.e., 2D vs. 3D).

10.2.4 Procedure

As participants arrived in the lab we introduced the study procedure and provided a brief explanation about highly automated driving. All participants, first completed a stereo vision test based on RDS (cf., Appendix II) to qualify for the study. After leading the test persons into the driving simulator, they could adjust seat, mirrors, and steering wheel in the car. The examiner explained how to activate highly automated driving as well as *Space Tetris*. Then the participants had the possibility to practice the game for five minutes.

The first drive served as a training drive to get familiar with the driving simulator, activating and deactivating highly automated driving and reacting on TORs. After the participants felt comfortable with the automated system as well as playing the game, we started one of the two test drives. All drives required the participants to drive on a highway with three lanes and medium traffic. After a few minutes of manual driving the examiner encouraged them to activate highly automated driving. Than the participant had the chance to play *Space Tetris*. All participants were motivated to maximize their score by making them aware of a price for the best player in the study. After playing the game for approximately six minutes the TOR situation occurred. Once the participants passed the situation they rated on a five-point Likert scale the perceived criticality of the take-over. Afterwards, the second test drive started which proceeded analogously to the first test drive. As the participants finished both test drives, the study ended by completing a demographic questionnaire. One test session took 45 minutes.

10.2.5 Participants

We recruited 47 participants (7 female, 40 male) aged between 17 and 43 years (M=28.0 year; SD = 6.2 years) via our internal mail system. All participants were in possession of a valid driving license. Ten were used to drive a car daily, while 19 drove at least once a week and 16 less than once a week (two participants did not specify their driving performance). We split the participants in four groups following our mixed study design. Group A (n = 12) used the 2D game and experienced the async variant in the first test drive and the sync variant in the second test drive. Group B (n = 12) experienced sync before async in 2D. Group C (n = 12) had the similar sync sequence as group A but played the 3D variant. Group D (n = 11) played the sync variant before async in 3D.

10.2.6 Measures

Beside the subjective rating of the criticality we gathered a bunch of objective data to evaluate the take-over process. The driving simulation logs the data with a frequency of 100 Hz. We clustered the objective measures due to timing and quality aspects following former research [123,142]. Table 10.1 gives an overview of the used measures. Regarding timing aspects we measured the time from the TOR until the driver grasps the steering wheel and until the first driver reaction (braking or steering) occurred. Assessing the take-over quality we measureed the type of driver reaction and lane change errors. As lane change errors we defined the neglected use of the rear-view mirror, the side mirrors, corridor checks, and the indicator when it came to a lane change maneuver. We evaluated missed glances at rear-view or side mirror and the corridor beside the car by a post-hoc

Table 10.1: Measures used in the study.

Aspect	**Variable**	**Definition**
Timing aspects of take-over process	take-over time [s]	Time until the actual driving maneuver begins, steering wheel angle $> 2^\circ$ or brake pedal pressure $>$ 10% [69]
	Hands on time [s]	Time until the driver grasps the steering wheel
Quality aspects of take-over process	Reaction type []	Distribution of reaction types (brake; steer; brake & steer)
	Lane change errors []	Use of rear-view mirror, side mirror, corridor checks, and indicator
	Longitud. acceleration [m/s^2]	Maximum longitudinal acceleration
	Lateral acceleration [m/s^2]	Maximum lateral acceleration
	Net acceleration [m/s^2]	Maximum net acceleration
	Deviation of driving trajectories [m]	deviation of driving trajectory (DDT) from mean trajectory
Subjective aspects	Criticality rating	Five-point Likert scale (1 = very low criticality; 5 = very high criticality)

video analysis. Moreover, we analyzed the maximum longitudinal, lateral, and net acceleration that affect the vehicle in its center of gravity. The net acceleration depends on the longitudinal (a_{long}) as well as the lateral acceleration (a_{lat}) as follows [173]:

$$a_{net} = \sqrt{a_{long}^2 + a_{lat}^2}$$

As a further measure of the take-over quality we introduce the deviation of driving trajectories (DDT). DDT allows to measure the differences of the driving trajectories. In our case, we are interested in the driving curve for the passing maneuver to avoid a crash with obstacles on the same driving lane. Note, that the DDT does not incorporate timing and velocity aspects of the driving maneuver. The basic idea of the DDT calculation is based on the measure of the standardized Lane Change Task (LCT) [108]. In contrast to the standardized LCT, we do not use a normative model as reference for the driving trajectories but a mean trajectory of the collected data. We argue that it is hard to define a normative model that represents the suitable trajectory for the used take-over scenario. Following the classical test theory, the true score is defined by the mean [32]. For this reason we use the mean trajectory over all participants and conditions as reference. Hence, the DDT describes the deviation from the mean driving trajectory rather than the most adequate driving trajectory.

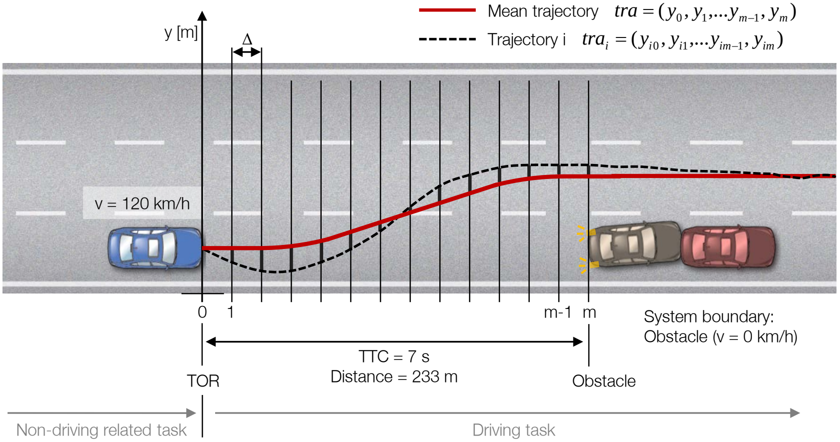


Figure 10.3: The TOR occurred 233 m in front of an accident. We calculated the DDT with a sample rate of $\Delta = .388$ m.

The calculation requires a formalization of trajectories which we define as follows: We compare a set of trajectories $T = \{tra_1, ..., tra_n\}$. A driving trajectory $tra_i = \{(y_{i0}), ..., (y_{im})\}$ consists of m data points representing the lateral position y_{ij} of the car. The data points between start and end depends on the length of the sample rate Δ defining the corresponding longitudinal data points of the trajectory (cf., Figure 10.3). The starting point of each trajectory y_{i0} is defined by the TOR (233 m longitudinal distance between car and obstacle) and its end y_{im} by passing the obstacle (0 m longitudinal distance between car and obstacle). Using the formal notation of trajectories we can calculate the DDT in two steps:

1. Calculating the mean trajectory: As reference trajectory we calculate a mean trajectory over all conditions and participants. For $T = \{tra_1, ..., tra_n\}$ containing n comparable trajectories the reference trajectory is

$$\overline{tra} = \{(\bar{y}_0), ..., (\bar{y}_m)\} \quad \text{with} \quad \bar{y}_j = \sum_{i=1}^{n} \left(\frac{y_{ij}}{n}\right).$$

2. Calculating the deviation from the mean trajectory: Now we can calculate for each trajectory tra_i the DDT:

$$DDT(tra_i) = \sum_{j=0}^{m} (|y_{ij} - \bar{y}_j|)$$

Table 10.2: Descriptive statistics (mean and standard deviation in brackets) of the continuous data measuring the take-over behavior.

Measure	**Condition (Visualization Synchronization)**			
	2D async	2D sync	3D async	3D sync
Hands on time [s]	1.082 (0.388)	1.039 (0.310)	1.215 (0.226)	1.184 (0.239)
Take-over time [s]	2.290 (72.4)	2.274 (0.798)	2.295 (0.643)	2.073 (0.521)
Longitud. acceleration [m/s^2]	3.700 (3.052)	4.001 (3.224)	1.782 (1.875)	2.545 (2.770)
Lateral acceleration [m/s^2]	1.954 (0.689)	2.265 (1.179)	1.644 (0.775)	1.832 (0.696)
Net acceleration [m/s^2]	4.448 (2.404)	4.796 (2.584)	2.582 (1.545)	3.426 (2.233)
Deviation of driving trajectories [m]	214.477 (129.994)	243.800 (100.022)	161.192 (70.268)	171.281 (72.828)
Criticality	4.333 (1.354)	4.762 (1.513)	4.158 (1.385)	4.421 (1.387)

For calculating the DDT we use a sample rate of $\Delta = .388$ m. Figure 10.3 depicts the necessary parameters for the calculation of the driving trajectories.

10.3 Results

We have to exclude seven participants from the analysis. Two of them lost the control over the vehicle during the first take-over scenario. For these persons the study ended after the first drive. The two participants belonged to Group B and D. Five persons already looked at the traffic scenery while the TOR occurred as a post-hoc video analysis shows. Since all participants should be initially confronted with the scenery at TOR we did not consider these five persons for the statistical analysis. Finally, the sample consists of 40 persons, 12 in Group A, 9 in Group B, 12 in Group C, and 7 in Group D. Table 10.2 shows the descriptive statistics for the continuous data measured during the study.

10.3.1 Timing Aspects

Figure 10.4 shows the data of the time measures for all four conditions. Looking at the hands on time the condition 2D sync shows the shortest reaction time compared to the other conditions. A two-way mixed ANOVA does not show significances for the visualization, $F(1,38) = 2.730$, $p = .107$, synchronization, $F(1,38) = .699$, $p = .408$, and visualization * synchronization, $F(1,38) = .016$,

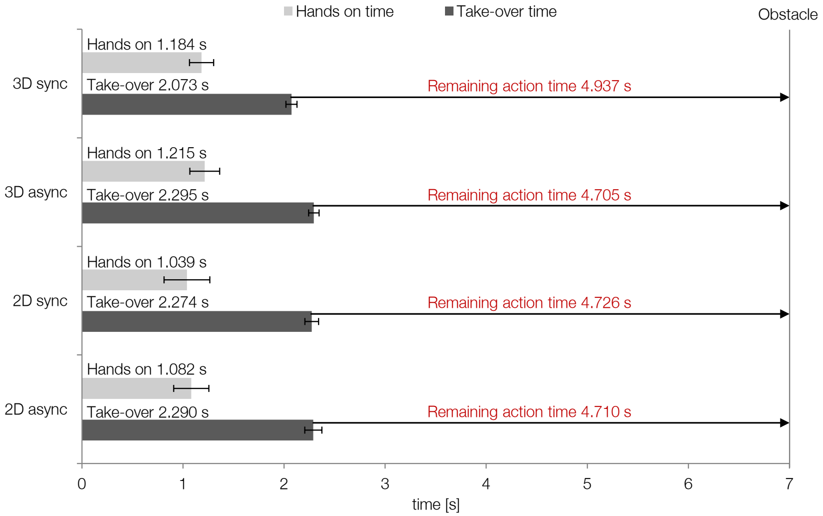


Figure 10.4: Means and standard errors for the hands on and take-over time.

$p = .900$. Despite the longer hands on time 3D sync reveals the shortest take-over time. However, a two-way mixed ANOVA does not reveal significant effects for the visualization, $F(1,38) = .234$, $p = .631$, synchronization, $F(1,38) = .683$, $p = .414$, and visualization * synchronization, $F(1,38) = .514$, $p = .478$.

10.3.2 Quality Aspects

Reaction types

We classified the reaction of the participants in three groups: *braking only*, *steering only*, and *braking and steering*. Figure 10.5 shows the distributions for the out four conditions. Looking at the variable synchronization, the distribution is quite similar between the sync and async variant. For the variable visualization, the 3D sample mainly used the steering wheel to cope with the situation. The 2D sample frequently used the brake while four participants even performed a full stop. Since we used a mixed study design, we analyze the effects of the independent variables separately. Comparing the distributions of the 3D and 2D sample, a chi square test shows significant differences between the samples, $\chi^2(2) = 5.730, p = .048$, Cramer-V=.268. However, the assumption of chi-square

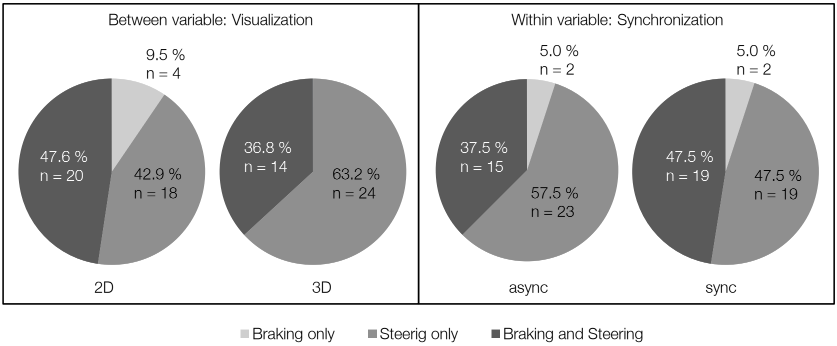


Figure 10.5: Reaction types for visualization and synchronization.

concerning "minimum expected cell frequency" is violated. Fisher's exact test does not show a significant effect, $\chi^2(2) = 5.408, p = .053$. The distribution of reaction types is not significantly different between the sync and async drives as a McNemar-Bowker test shows, $p = .102$.

Lane Change Errors

Since the video recording failed for eight participants the statistical analysis is based on the remaining sample of 32 persons with 10 in Group A, 7 in Group B, 10 in Group C, and 5 in Group D. Note, that the indicator data is recorded by the simulator and hence comprises the sample of 40 participants. In accordance

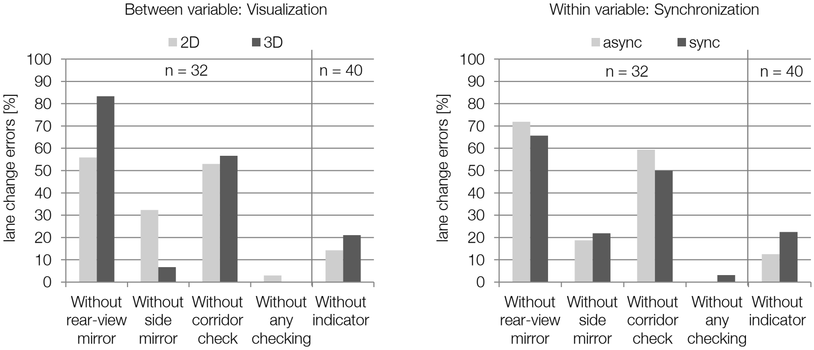


Figure 10.6: Lane change errors for visualization and synchronization.

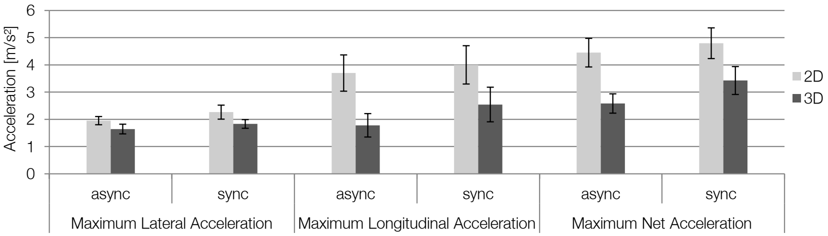


Figure 10.7: Means and standard errors for the maximum accelerations.

with the analysis of the reaction types, we separately analyze the two independent variables visualization and synchronization. Figure 10.6 shows the number of lane change errors for the between and within variable. The diagrams show that the participants generally secured the lane change by glances and the use of the indicator. Regarding the between variable visualization, the 3D sample used the side mirror more frequently while the 2D sample looked more often in the rear-view mirror. Chi-square tests show significant differences in the use of the rear-view mirror, $\chi^2(2) = 5.590, p = .018, \varphi = .296$, and the side mirror, $\chi^2(2) = 6.496, p = .011, \varphi = -.319$. Analyzing the checking of the corridor, the general use of visual checks, and the use of the indicator do not show significant differences, $p \geq .531$. Analyzing the two levels of synchronization with McNemar tests shows no significant effects for the use of the rear-view mirror, the side mirror, the checking of the corridor, the general use of visual checks, and activating the indicator, $p \geq .125$.

Acceleration

Figure 10.7 depicts the descriptive statistics of the maximum longitudinal, lateral, and net acceleration. It reveals higher acceleration values for 2D than 3D. The condition 2D sync reveals the highest accelerations. A two-way mixed ANOVA shows that there is a statistically significant main effect for the synchronization, $F(1,38) = 4.798$, $p = .035$, $\eta = .112$, as well as visualization, $F(1,38) = 6.094$, $p = .018$, $\eta = .138$, but no interaction effect, $F(1,38) = .832$, $p = .367$, for the net acceleration. Regarding the longitudinal acceleration there are no significant effects for synchronization, $F(1,38) = 3.414$, $p = .072$, visualization, $F(1,38) = 4.052$, $p = .051$, and their interaction, $F(1,38) = .643$, $p = .427$. The same applies for the lateral acceleration as the ANOVA shows no significances for synchronization, $F(1,38) = 2.901$, $p = .097$, visualization, $F(1,38) = 2.572$, $p = .117$, and their interaction, $F(1,38) = .179$, $p = .675$.

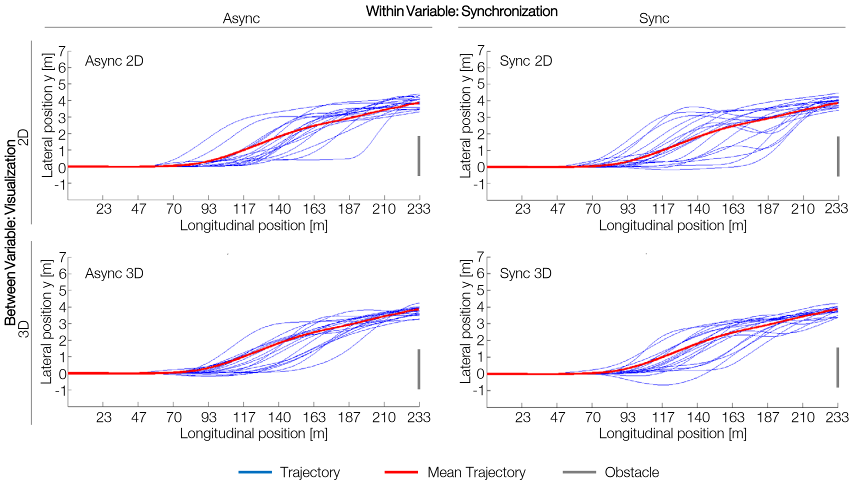


Figure 10.8: Driving trajectories for each test condition. The trajectories of the 2D sample show greater deviations from the mean trajectory driven by all participants which is depicted by a red line.

Trajectories

We are interested in the driving trajectories for those participants choosing to overtake the obstacle rather than braking. Therefore, we excluded the data of the four participants that braked only for analyzing the driving trajectories. As a result, the statistical analysis is based on ten participants in Group A, eight in Group B, eleven in Group C, and seven in Group D. Figure 10.8 shows the driving trajectories for each test condition. This diagrams indicate that the trajectories for the 3D sample are closer together while the ones of the 2D group reveal great variances. For a statistical analysis of the trajectories, we calculated the DDT as mentioned earlier. Figure 10.9 presents the descriptive statistics of the calculated DDT. In accordance to the plots of the trajectories (cf., Figure 10.8), the DDT shows lower means for the 3D than for the 2D conditions. A two-way mixed ANOVA shows a significant impact of the visualization, $F(1,38) = 5.457$, $p = .026$, $\eta = .138$. The main effect for synchronization, $F(1,38) = 1.297$, $p = .263$, as well as the interaction of visualization and synchronization are not significant, $F(1,38) = .309$, $p = .582$.

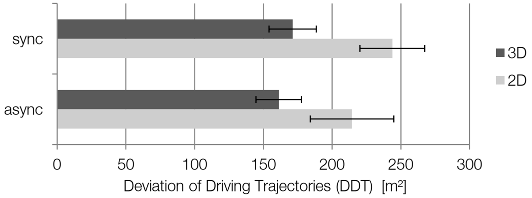


Figure 10.9: Means and standard errors for the deviation of driving trajectories (DDT).

10.3.3 Subjective Findings

Four participants recognized the synchronization of the game objects with the driving scene (one in Group A, one in Group B, and 2 in Group C). They mentioned this feature as “helpful" for the take-over scenario and felt “optimally prepared". In general, the participants rated the conditions pretty similar in their criticality. A two-way mixed ANOVA shows no significant differences for the criticality rating on visualization, $F(1,38) = .413$, $p = .524$, and synchronization, $F(1,38) = 3.083$, $p = .087$, as well as their interaction, $F(1,38) = .176$, $p = .677$.

10.4 Discussion and Limitations

We conducted the presented study in a high-fidelity driving simulator that provides kinesthetic feedback. However, the simulation does not perfectly match real world environments. Hence, variables such as acceleration can slightly differ from reality. Moreover, we want to emphasize that the presented user study covers one particular take-over scenario. Knowledge about the generalization of take-over scenarios is in inherent need.

The findings indicate that the similarity between the non-driving related task and the driving scenario does not significantly impact hands on and take-over times. On average, the participants started a maneuver after 2.2 seconds. This finding is in line with take-over times of prior experiments [69, 142]. However, the 2D sample tends to grasp the steering wheel earlier than the 3D sample. A possible explanation for the delayed physical reaction is that a 3D visualization of games, particularly when using stereoscopic cues, increase the user experience and immersion [206, 263]. Nevertheless, the take-over time tends to be lower for the 3D sample driving with the synced version of the game. This condition provides the highest level of similarity.

In contrast to the results addressing timing aspects, we found a significant influence of the task's similarity on the take-over quality. In general, the outcomes show that the spatial visualization has a greater impact than the synchronization of the UI objects with the driving scene. This is reflected by the finding that just four participants noticed the synchronization. Moreover, the synchronization does not significantly impact the reaction type as well as lane change errors. In contrast, the type of visualization shows an impact on both measures reaction type and lane change errors. While the 2D sample chose more frequently to use the brake and even performed full stops before overtaking, the 3D sample mainly decided to change the lane solely using the steering wheel. Gold et al. [69] states that the usage of the brake reduces speed in order to gain more time for making a proper decision or performing the passing maneuver. They argue that those reactions occur due to a lack of time to make the lane change or a poor situation awareness. Following their argumentation, the 3D visualization increases the situation awareness and supports the information processing of the driver to come to a proper decision. This finding is supported by the analysis of the lane change errors. In contrast to the 2D sample, the 3D sample used more frequently the side mirror than the rear-view mirror to securely change the lane instead of braking. As a further quality measure, the acceleration is significantly lower for the 3D visualization of the game. Following Gold et al. [69], higher accelerations imply riskier lane changes. Thus, we can accept hypothesis H1.

The acceleration data show also an effect for the synchronization variant of the game indicating a worse take-over quality for the sync observation. We assume that this result has less origin in the synchronization of game objects with the traffic participants in the driving scene but rather in the chosen async behavior of the game. Note, that the async variant of the game triggers a defined procedure of the game objects 30 seconds before the TOR occurs. Shortly before the TOR the sync procedure of the game makes the player aware of the possibility to collect two items that represent the upcoming obstacle. For this particular moment, the async procedure provides a rather boring game situation that does not allow the collection of tokens in the near future. We believe that this decreases the gamer's level of engagement resulting in a slightly improved take-over quality. Nevertheless, further experiments have to investigate the impact of engagement, which can be of visual but also solely of cognitive nature. Finally, as the take-over quality significantly improves for the 3D visualization we can accept H1. Nevertheless, our data do not reveal any indication of improving the take-over behavior due to the synchronization. Hence, we must reject H2.

Finally, we presented the DDT as a measure of the driving trajectories. Recent work [69, 123, 142] reported plots of the trajectories representing the take-over behavior. They interpreted the data by a visual inspection rather than a statistical analysis. The calculation of the DDT allows us to determine statistically significant differences between the conditions with the mean reaction as reference. The results show a significantly greater deviation of trajectories from the mean trajectory of the 2D sample in comparison to the 3D sample. In contrast, the levels of synchronization have no impact. We interpret the higher deviations as a result of an increased demand in choosing a proper reaction. This finding is in line with the other used measures evaluating the take-over quality such as reaction type, lane change errors, and acceleration. Hence, we assume that the DDT is a valid measure in order to compare driving trajectories for the applied take-over scenario. However, further studies have to investigate different variants of calculating the DDT (e.g., by using a normative model instead of the mean trajectory) and need to prove its reliability and validity.

10.5 Summary

Highly automated driving requires to rethink the UI of the car. On the one hand, the UI that represents the automation system itself should maximize take-over behavior as well as situation awareness. On the other hand, we argue that applications that the driver uses while the car takes care of the driving task should be designed in a way that facilitates the take over for the driver when it comes to a TOR. The challenges for the development of UIs that are used while highly automated driving differ from those used while manual driving. A lot of research, standards, and conventions exist for the latter driving level whereas little is known about the impact of the non-driving related task when the car drives highly autonomous.

As a first step, we investigated the similarity between the non-driving related task and the driving scenery when it comes to an unexpected TOR. The results show that a visual similarity has not a significant impact on the time required for starting a maneuver but significantly increases the take-over quality. In particular, a spatial visualization similar to the driving scene improves the take-over quality. Adapting temporal aspects, such as the position of the UI elements in accordance with the traffic participants, has not a significant impact on the take-over behavior. As a result, we recommend to depict the spatial layout of the traffic scenery in the non-driving related task in order to foster the driver's take-over behavior. For example, a UI menu can be spatially structured showing lists along the depth axis rather than applying 2D elements. Note, that we compared a visualization incorporating monoscopic as well as stereoscopic depth cues against a visualization without any depth cue. Hence, we are not able to state which depth cue should be inherently used and which one is optional. Further investigations need to clarify the impact of stereoscopy in contrast to monocular depth cues. In particular, a real world driving study has to verify our results. Driving through a real 3D environment rather than simulating this task on a virtual monocular projection can have an impact on the spatial presence induced by a 3D visualization. Beside the visualization we assume that the level of interruptibility of the non-driving related task as well as the display location and the interaction modality have an impact on the take-over behavior. Further investigation is in need that examines hand held devices and typical display locations in the car as well as characteristic interaction techniques such as direct and remote control.

VI

CONCLUSION AND FUTURE WORK

Chapter 11

Conclusion

This thesis explores the use of S3D for in-car UIs. The goal is to support developers in adding value to their UIs by using 3D displays and to identify opportunities and risks. In the following, we summarize the contributions of this thesis, point towards future directions of research in the fields of S3D UIs and automotive UIs, and provide a final statement about the in-car use of 3D displays.

11.1 Summary of Research Contributions

The literature review presented in Section 2.3 identified opportunities and challenges of S3D. Beside increasing the naturalness and attractiveness of the system, S3D allows for structuring information and supports the understanding of spatial elements. However, the S3D effect can evoke visual discomfort due to the presented content. Hence, a well-considered depth layout is necessary to benefit from its usage. This requires to take the 3D layout into account from the very beginning of the development process. Prior work mainly explored specific aspects of S3D with no regard to its integration into the development process of the UI. To fill this gap, we explored S3D for automotive UIs contributing to several stages of the user-centered design process. In this way, we provide novel insights into the design of S3D UIs and unfold chances and challenges for an in-car use. In the following, we outline the three major contributions of this thesis and provide answers to the initially defined research questions in Table 11.1.

Table 11.1: Overview of Contributions on Research Questions.

No.	Research Question
	I. Design principles
R1	**Which 3D layout supports a comfortable viewing experience?** Excessive parallaxes are the main reason for visual discomfort due to the decoupling of accommodation and convergence. As literature suggests highly different parallax limits, we conducted two lab studies revealing concrete comfort zones for near as well as far-viewing displays (cf., Chapter 4). Besides, we found that reference objects on screen depth strongly decrease interindividual variances and also result in a narrower comfort zone than showing only one single object in space.
R2	**How do 3D parameters affect the depth perception?** Based on our defined comfort zone limits, we conducted four lab studies to evaluate the perception of S3D. This approach allowed us to derive several design principles for arranging objects in 3D space addressing the characteristics of a IC and HUD (cf., Chapter 5). Most notably, the use of negative parallaxes hamper the instant perception of fine depth differences for near-viewing displays as the IC. In regard to a HUD, S3D allows the precise judgment of real world depth.
	II. Prototyping Tools
R3	**How can we extend paper prototyping for 3D user interfaces?** We presented two tools for paper prototyping 3D depth layouts, the FrameBox and the MirrorBox. As the FrameBox allows an accurate arrangement of several depth layers in a cubic box, the MirrorBox solely supports the design of three separate layers. Particularly, the FrameBox enhances paper prototyping by encouraging the exploration of a definite 3D space while the MirrorBox mainly contributes to the perceived fidelity of the prototypes (cf., Chapter 6).
R4	**How can computer-based tools support prototyping for 3D Displays?** Instant visual feedback about the 3D layout is essential for prototyping in 3D space. We iteratively developed two concepts with different objectives (cf., Chapter 7). The first concept targets a collaborative use as the design of the UI occurs on a 2D screen while a 3D display simultaneously visualizes the 3D output. The second concept uses one 3D screen for directly prototyping the S3D layout and provides solutions for interacting in 3D space.
	III. Automotive Application Domain
R5	**How does 3D depth impact on task performance while driving?** We investigated the use of S3D for highlighting important information and judging virtual distances in a driving simulator (cf., Chapter 8). We were able to show that S3D decreases reaction times on popping-out instructions and increases depth judgments while driving. Driving performance as well as gaze behavior were not affected by the S3D visualization.
R6	**How do drivers perceive the 3D effect while driving through the real world?** We equipped a vehicle with a 3D display as IC and conducted two real road studies (cf., Chapter 9). We obtained detailed insights on the use of S3D in cars which are hard to find in the simulator. In general, the driver is not confused by frequently switching the visual attention between the real 3D driving environment and a S3D IC. In particular, S3D supports the mapping between the real and virtual 3D world, while the motion of the car unfolds shear distortions which attract negative attention. Nevertheless, S3D proves a high acceptance due to its pleasant appeal.
R7	**How does 3D influence the take-over behavior for highly automated driving?** We contributed a novel approach which adapts the 3D layout of a non-driving related task to the current driving situation with the goal to prime the driver for driving when it comes to a TOR (cf., Chapter 10). A study in a high-fidelity simulator showed that a S3D visualization compared to a pure 2D display, which provides no depth information at all, effectively supports the driver to reengage in the driving task. However, positioning the UI elements in accordance with the traffic participants shows no effect on the take-over behavior.

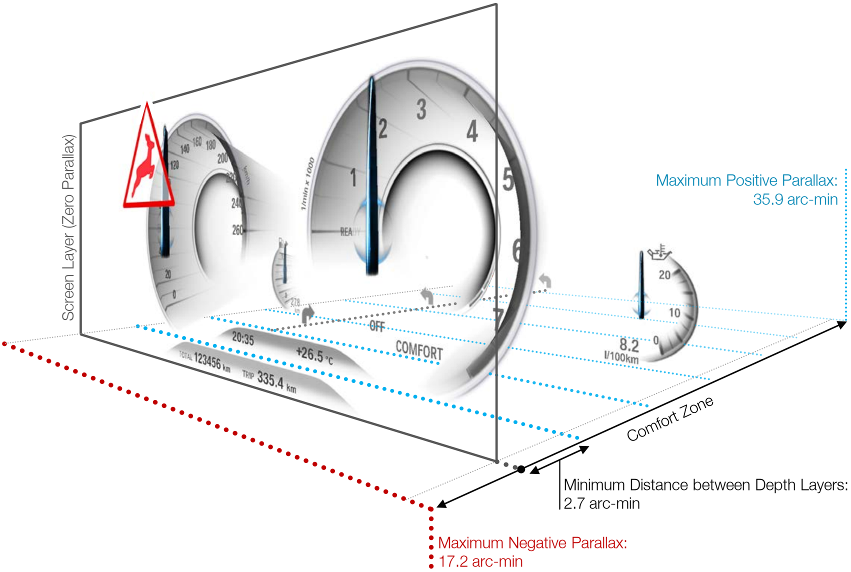


Figure 11.1: Schematic illustration of design principles for a S3D IC.

11.1.1 Design Principles

For beneficially using S3D depth in a UI it is essential to choose proper depth positions. The depth layout has to fulfill two simple requirements. First, the user should be able to comfortably fuse the applied screen parallaxes. Second, the S3D effect should allow for quickly and unambiguously identifying the depth layout. We conducted several user studies in a laboratory environment which allowed us to formulate a set of design principles. In general, we recommend the approach of, first, determining a comfortable depth range before investigating the depth perception within this comfort zone. The setup of the studies addressed two typical display locations in the car, the IC and the HUD. Although our approach allows for using the defined principles for several application areas, we demonstrate their application on the domain of automotive UIs in the following.

Instrument Cluster

Figure 11.1 outlines the findings of our studies concerning a 3D IC and provides exact values for the comfort zone and minimal distance between depth layers.

While negative parallaxes should be used carefully, we recommend positive parallaxes to maximize depth perception. As a result, elements which represent spatial relations, such as navigation cues, should be displayed behind the screen plane. Elements with zero parallax clearly set the screen layer as important reference for perceiving the displayed 3D volume. We recommend to display elements requiring a high readability on the screen layer which is not affected by stereoscopic distortions such as crosstalk. In general, structuring information via depth should consider the available 3D space as a whole including vertical and horizontal positions, as well. Nevertheless, we recommend to use a maximum of six information layers to avoid spatial clutter. While the additional use of monoscopic cues generally fosters the depth impression, motion parallax is not recommended for automotive applications as it decreases the perceived readability due to its hectic and reactive behavior.

Head-Up Display

We envision a 3D HUD for showing vehicle related information (e.g., speed, infotainment lists) on a depth layer close to the vehicle while superimposing the real world with information related to the driving environment (e.g., navigation cues, ACC). Therefore, we recommend a virtual screen distance between 5 and 8 m which allows the comfortable presentation of depth ranges from 3 up to 20 m in front of the driver. In general, judging depth of real world objects occurs highly accurate solely based on a S3D effect in the HUD. This points towards a reliable augmentation of the real world using S3D as a depth cue.

11.1.2 Prototyping Tools

In general, developing UIs for 3D displays is considerably more complex than for 2D displays. Beside reflecting the intended value of the 3D effect for the UI (e.g., S3D for structuring information, as spatial metaphor for abstract UI elements, or for increasing the naturalness of a virtual environment), the developers need to adhere to design principles to come up with a comfortable and usable S3D interface. Based on the design principles we identified for structuring information using S3D depth, we developed tools which support the early prototyping of 3D layouts. We implemented and evaluated both paper prototyping tools, the FrameBox and MirrorBox, as well as computer-based tools, the S3D-UI Designer and S3D-HUD Designer.

Paper Prototyping

In particular, the FrameBox demonstrates its usability for creatively exploring the available 3D space. It supports the proper use of depth layers for structuring information but also the integration of 3D objects which extend into depth. In contrast, the MirrorBox is limited in its design space as it supports solely three separate depth layers. Moreover, using the MirrorBox for paper prototyping unfolds a decreased usability as the positioning of the sketched layers is cumbersome. Nevertheless, the MirrorBox contributes to the perceived fidelity of the prototypes and also allows the development of digital prototypes.

Computer-based Prototyping

The idea behind the presented computer-based tools is to provide the developer instant feedback about the designed 3D layout. Our developed tools meet this requirement by applying two different concepts. First, the S3D-UI Designer allows for several depth layers to be designed on a 2D display while a 3D output device instantly mirrors the resulting S3D representation. This concept supports the usage of well-known 2D interaction principles for designing a 3D depth layout. In particular, this concept supports structuring information on separate depth layers. Second, the S3D-HUD Designer uses one 3D screen for visualizing the interface of the prototyping tool and the resulting S3D layout. The presented concept is suitable for prototyping UI overlays for virtual, mixed, and augmented reality applications. However, it requires the designer to interact in 3D space for arranging the UI elements. A user study demonstrates that conventional 2D input devices as the mouse already provide a high usability for manipulating objects in 3D space while gesture interaction might further improve 3D interaction.

11.1.3 Automotive Domain

The automotive domain faces a paradigm shift from manual to automated driving. Section 3.2 highlights the fundamental changes in requirements for the in-car UI based on different automation levels. While the distraction caused by the UI is important for manual driving, the impact of the in-car UI on the driver's take over behavior is decisive for highly automated driving. As a result, we evaluated the S3D effect for both driving modes, manual and highly automated driving. Therefore, we developed proper S3D IC concepts by applying our postulated principles and our prototyping tools. Since all of our studies reveal clear advantages for a

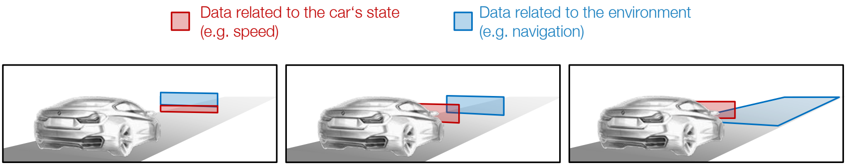
3D visualization in comparison to its monoscopic counterpart the applicability of both the requirements and the prototyping tools is further validated.

Manual Driving

We conducted studies in a driving simulator and in real world environments. All studies show that the S3D effect is well accepted as it contributes to declutter and structure the presented content and increases the user experience. Moreover, we found in the simulator that the highlighting of instructions using S3D accelerates the driver's reaction. This identifies the ability of S3D for communicating urgency. A real road study validates this finding. Although color shows a greater impact on communicating urgency than S3D, the combination of both maximizes the visualization of urgency. Moreover, S3D helps in judging distances visualized in the IC and allows for an easy translation between the real and virtual 3D world. Thus, navigation cues as well as the distance to the preceding car are conveyed in an intuitive way. However, shear distortions are apparent due to the dynamics resulting from driving through real environments and need to be eliminated by distorting the image according to the viewer's position. Shear distortions are one reason for discomfort. Our data shows that sickness symptoms slightly increase due to the 3D effect. Nevertheless, although the perceived workload often tends to be slightly higher while using a S3D visualization there is no evidence for a significant impact on the driving performance. As we did not test crucial driving scenarios which immediately require all cognitive resources of the driver, this is left for future work.

Highly Automated Driving

Spatial and temporal awareness are key factors for properly maneuvering the car through a dynamic 3D environment. Consequently, interacting and orientating in virtual S3D space has common aspects with the driving task. We claim that the similarity between the driving task and a non-driving related task contributes to switching between both. Indeed, we could show that the quality in taking over the driving task significantly improves if the driver has been engaged in a 3D task that address similar spatial layouts as the driving environment. As a conclusion, the use of 3D displays during highly automated driving allows an immersive entertainment using in-vehicle displays while the a proper 3D layout can contribute to the reorientation in the driving environment in the case of take-over scenarios.



(a) All information on one depth layer (b) Two depth layers with monoscopic augmentation (c) Stereoscopic augmentation

Figure 11.2: Three depth layout concepts for an AR HUD.

11.2 Future Work

The research presented in this thesis points to various directions for future research. In the following, we highlight challenges for prospective short but also long term projects on S3D and automotive UIs.

11.2.1 AR HUD

Our laboratory study in Section 5.4 shows that S3D enables a highly accurate depth mapping between the virtual and real world. Nevertheless, insights on the direct comparison between a monoscopic and stereoscopic augmentation of the real world and the impact on manual and highly automated driving are missing.

For manual driving, we envision the comparison of three depth layout concepts, outlined by Figure 11.2. The first concept (cf., Figure 11.2 (a)) represents one depth layer which shows status information (e.g., speed, incoming call) as well as content that concerns the driving environment (e.g., navigation cues, distance to preceding car, lane keeping assistant) solely using monocular cues. The second concept (cf., Figure 11.2 (b)) involves two depth layers. The foremost layer shows the status information close to the vehicle while the second layer augments the real world using monocular cues. Finally, the third concept (cf., Figure 11.2 (c)) shows status information on one depth layer close to the vehicle while the real world is superimposed at the appropriate 3D location. The comparison of these concepts is challanging. As a first step, the S3D-HUD Designer (cf., Section 7.3) can be used for developing the three UI designs and a preliminary evaluation. However, the major point of interest for a 3D HUD is the interplay between the real 3D world and the artificial 3D effect. Thus, an evaluation in the real world is absolutely necessary to understand the effects of a 3D HUD while driving.

As a result, an evaluation in the simulator, providing an artificial 3D driving environment as well, is not sufficient but can provide valuable insights.

Regarding highly automated driving, it is worthwhile to investigate the impact on a take-over scenario while interacting on several depth layers compared to solely using one plane in the HUD. This requires the conceptualization of a utilitarian (e.g., e-mail manager) or entertaining (e.g., game) application which contextually overlays the driving scene, for example, close traffic participants in their 2D or 3D position. A 3D augmentation could foster the driver's spatial and temporal situation awareness. In turn, the 3D effect might improve the spatial orientation of the driver and hence could impact the take-over performance. However, an ultimate understanding of those scenarios also requires an evaluation in the real world. As the development of such a test vehicle is highly complex a proper evaluation method on a testing route has to be considered. In addition, a preliminary study in a 3D simulator can deliver first insights.

11.2.2 S3D for other Application Domains

In this thesis, we deliberately investigated the use of S3D for automotive applications. Nevertheless, the exploration of the S3D effect for other application domains is promising as well. As the use of S3D for gaming was well studied by Schild [204], we identified three additional interesting application areas. First, the use of autostereoscopic multiview S3D displays enables a proper 3D experience in public spaces. The S3D effect can attract the attention of passers-by and might be an affordance for an embodied interaction with public displays. Exploring interaction techniques and the impact of 3D on audience behavior, user acceptance, experience, and presence is highly interesting for future work. Second, research on S3D menu navigation for mobile devices is still scarce. Autostereoscopic technology constantly improves and Samsung is currently working on an 11K 3D display[44]. Exploring interaction techniques and user acceptance of S3D menus for mobile devices are research challenges that need to be addressed in the future. Third, TVs are increasingly equipped with autostereoscopic screens but 3D has not been established in the TV infrastructure yet. However, the availability of quite a number of TV programs as well as online access considerably increases the complexity of the TVs' UI. Proper remote interaction and visualization techniques exploring the potentials of S3D represent promising research directions for the area of TV UIs.

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[44] http://www.digitaltrends.com/mobile/samsung-11k-screen-news/ last accessed September 20, 2014.

11.2.3 Interaction with 3D Displays

While this thesis focuses on the impact of a 3D display for visualizing information structures in GUIs, it is highly interesting to explore proper input modalities for interacting in 3D space. In Section 7.3 we already explored mid-air gestures for manipulating objects in 3D space. Although mouse input outperformed the applied gestures we assume that improving the gesture interaction can unfold its potential for interacting in 3D space. Regarding touch, a direct manipulation of UI elements with positive parallaxes is not possible as the screen blocks the user's hand of touching the respective screen layer of the object. In addition, touching elements with negative parallax needs solutions for haptic feedback, for example, using ultrasounds [37]. A possible interaction technique for touching negative and positive parallaxes could be to physically move the display's surface towards the depth layer which is intended for a direct manipulation. Moreover, selecting objects in S3D can occur via gaze input as the pupil distance can indicate the gaze point in 3D space [5]. An intelligent combination of gaze with further modalities such as mid-air or touch gestures point to promising future directions for interacting with S3D visualizations.

11.2.4 Automatic Adaption of the Depth Layout

The adaption of the depth layout due to the user's state and behavior is an interesting research direction. Bernhard et al. [13] showed that a dynamic adjustment of extreme parallaxes due to the gaze behavior of objects can lower fusion times in foveal vision. As fusion limits increase in the peripheral vision [129], adjusting the depth budget due to the gaze position of the user seems promising. Hence, for an automotive head-down display the applied parallaxes can increase if the driver looks at the driving scene and decrease if the gaze falls onto the S3D display. In this way, the S3D effect can be used for enhancing peripheral stimuli. Future research has to investigate the perception of peripheral S3D stimuli in regard to their impact on workload and visual comfort. Moreover, the simulation of focal blur due to the user's 3D gaze point might have a positive impact on viewing comfort and the naturalness of the S3D scene. In general, we explored the perception of S3D stimuli in dual task conditions and rather short exposures (up to 20 minutes) in this thesis. An interesting question is how the user/driver perceives S3D content in highly demanding and critically situations as well as for prolonged exposures. Maybe the S3D perception breaks down due to cognitive overload in stressful situations. In addition, possible discomfort increases for prolonged exposures [129]. If the users' workload and comfort can be reliably predicted or measured in real time, the presented parallaxes can automatically adapt to the user's state.

11.2.5 Comparing S3D with Real 3D Displays

As S3D display technologies do not support accommodation, accommodation-convergence mismatches are one main cause for visual discomfort and fatigue. In contrast, real 3D displays readily support further depth cues, also those which are not native for S3D displays such as accommodation, depth of focus, and motion parallax. However, volumetric and holographic technologies are still objects of research and have not been commercialized yet. Recent developments in combining light field and stereoscopic technologies [100] bring real 3D displays closer to the consumer market. The use of multi-layer displays (MLDs) allow for presenting information on several depth layers but limit the 3D design space to defined layers. Future research needs to clarify which potentials and challenges MLD as well as emerging light field technologies provide in comparison to S3D displays, for example, in regard to gaze behavior, spatial perception, and viewing comfort. In addition, current research investigates displays that can dynamically change their physical 3D shape [84, 135]. These *shape displays* provide novel means for interaction by supporting a spatial output and a direct input which provides real haptic feedback. In particular, we assume that physical 3D displays can enhance in-car UIs as the direct embodied interaction has the potential to decrease driver distraction in terms of workload and eyes-off-the-road time. In general, assessing and comparing the design spaces of these diverse technologies (i.e., S3D, volumetric, MLD, physical 3D displays) could provide crucial guidelines for choosing the proper 3D technology in accordance with the intended application.

11.2.6 The Advent of Automated Driving

With the advent of automated driving the requirements considerably shift for automotive UIs as Section 3.2 demonstrates. In the following, we outline three research challenges among the broad range of rising questions on the role of in-car UIs for automated driving. First, the investigation of issues related to road safety is necessary. Level 3 automation allows the driver to draw the full attention on non-driving related tasks but also requires the driver to reengage in the driving scenario if necessary. In this case, the UI has to optimally support the driver in shifting the attention from the non-driving related to the driving task. Reliable methods and standards are required which enable the evaluation of future concepts. Second, if the vehicle supports several automation modes the UI needs to convey a clear and comprehensive communication of the current automation mode. The driver needs an explicit internal representation of their and the car's current responsibilities and when it is possible or even necessary to switch the automation mode. If the driver is not aware of their current role in the driving task serious consequences can arise which might also affect road safety. In addition, a well-considered UI representing the car's capabilities can impact on automation trust which plays a crucial role in the acceptance of automated vehicles. Third, high automation levels allow the driver to engage in non-driving related tasks. This offers new opportunities for the in-car UI such as providing immersive experiences with games and movies, an optimal environment for working, as well as the support of the interaction with other people in- and outside the car. This challenges the whole design space of vehicles as new input and output technologies as well as unconventional layouts of the interior (e.g., display locations, seating arrangement) are possible. A large body of work is required to explore those novel opportunities of in-car interaction with the ultimate goal to maximize the quality of the time which people will spent in automated vehicles.

11.3 Concluding Remarks

During the years I have worked on this thesis, there was one question which was frequently asked by colleagues at industry and university, researchers at conferences, as well as friends and family:

> "Do we need 3D displays inside cars?"

3D displays have been already presented in show and concept cars in the competition among car manufacturers for innovation leadership. If autostereoscopic technology further advances, we expect that future vehicles are equipped with such displays. However, it is crucial to understand the opportunities and challenges of these devices in cars and how the in-car UI can benefit from the 3D effect. This thesis shows clear advantages of S3D displays for an in-car use by tackling challenges such as visual discomfort and prototyping for 3D displays. Beside an improvement of user performance in secondary tasks while manual driving and take-over quality for highly automated driving, 3D displays enable a natural and joyful user experience. This clearly sets the users' preferences towards the use of binocular cues. Indeed, beside a well-considered depth layout the display technology is a key factor for the broad acceptance and adoption of 3D displays. If affordable and high quality 3D technologies enter the market and become a standard in consumer electronics, people will expect these technologies also inside their cars. As current autostereoscopic displays still lack in quality and are considerably more expensive than conventional 2D displays, MLDs are a reasonable approach towards 3D UIs in cars of the near future. Kia impressively presents a multi layer IC in their GT concept[45]. For the long term, we envision that 3D display technologies provide a seamless and fully natural 3D imaginary. Ten years ago, Dodgson [54] has already outlined the uncertainty about the general adoption of 3D displays in our everyday life:

> ”When we reach the point where an autostereoscopic display becomes available that offers the same quality as a conventional display for about the same price, autostereoscopic displays might break out of their niche markets. However, it is unclear whether 3D display will ever become the norm, taking over from 2D in the way that talking pictures replaced silent movies and color replaced black-and-white movies and television.”
>
> – **Neil A. Dodgson** (2005) [54]

In conclusion, this thesis provides fundamental insights in the development of S3D UIs for cars. At the same time it is obvious that the contributions of this thesis are solely temporary solutions in the fast moving field of HMI. We approach an exciting future of cyber physical systems in which the automotive domain rapidly moves towards fully automated vehicles while novel input and output technologies blur the boundaries between the analogue and digital world. It is up to us, HCI, HMI, and human factors researchers, to identify the optimal design parameters which ensure an ideal interaction with this increasingly digital world.

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[45] http://www.kia.com/eu/future/kia-gt/, last accessed September 24, 2015.

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APPENDIX

Appendix I: Relationship between Comfort Zone and Depth of Focus

Lambooji and IJsselsteijn [129] base their recommendation of comfort zone limits on the characteristics of depth of focus. We can transform the limits in diopters (DOF) to limits in angular disparity (δ) for a given viewing distance in meters (d_{meter}). Figure 3 outlines the area of sharp vision.

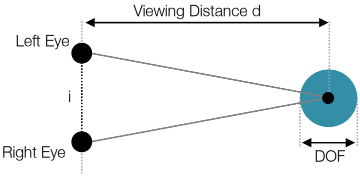


Figure 3: DOF describes the area in which objects are perceived clearly although accommodation does not change [129].

First, we transform the distances in the right units [177]:

Viewing distance in diopters: $d_{diopter} = 1/d_{meter}$
Closest point to viewer in meters: $\text{Near}_{meter} = 1/(d_{diopter} + \text{DOF})$
Farthest point to viewer in meters: $\text{Far}_{meter} = 1/(d_{diopter} - \text{DOF})$

Second, we calculate the angular disparity in front of the fixation point (crossed disparity):

$$\begin{aligned}\delta_{crossed} &= |\alpha - \beta| \\ \alpha &= 2 * arctan(\mathrm{i}/(2 * \mathrm{d}_{\mathrm{meter}})) \\ \beta &= 2 * arctan(\mathrm{i}/(2 * \mathrm{Near}_{\mathrm{meter}})) \\ &= 2 * arctan((\mathrm{i}/2) * (d_{diopter} + \mathrm{DOF}))\end{aligned}$$

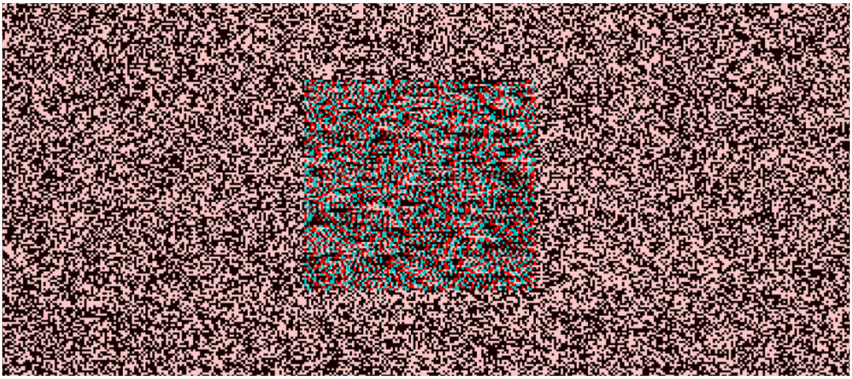
Third, we calculate the angular disparity behind the fixation point (uncrossed disparity):

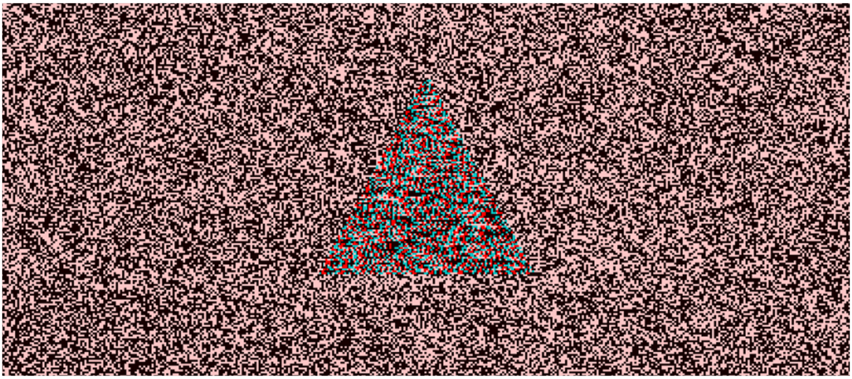
$$
\begin{aligned}
\delta_{uncrossed} &= |\alpha - \beta| \\
\alpha &= 2 * arctan(\mathrm{i}/(2 * \mathrm{d}_{\mathrm{meter}})) \\
\beta &= 2 * arctan(\mathrm{i}/(2 * \mathrm{Far}_{\mathrm{meter}})) \\
&= 2 * arctan((\mathrm{i}/2) * (d_{diopter} - \mathrm{DOF}))
\end{aligned}
$$

Lambooji and IJsselsteijn [129] assume 0.33 D as an accepted range for the depth of focus. Given a viewing distance $d_{meter} = 0.75$ m, an interocular distance $\mathrm{i} = 0.06$ and the assumed limits in diopters DOF = 0.33 D the calculation results in treshholds for crossed $\delta_{crossed} = 67.93$ arc-min and uncrossed disparities $\delta_{uncrossed} = 67.98$ arc-min. Lambooji and IJsselsteijn [129] recommend disparity limits of 1° as a conservative application of the 60 to 70 arc-min rule of thumb [262].

Appendix II: Random Dot Stereograms

In our studies, we tested the participants ability in stereo vision by presenting them several RDS shapes. If the participants could correctly identify the shapes as well as their depth position (i.e., behind or in front of the screen) they passed the test. The following RDS can be viewed using red-cyan glasses. The upper RDS depict a square placed behind the screen and the lower RDS shows a triangle in front of the screen.





Appendix III: Demographic Questionnaire

Studie zur Tiefenwahrnehmung

Teilnehmer Nr. _________ Datum _________

Demografischer Fragebogen

Alter

Geschlecht

Beruf

Abschluss

Haben Sie eine Sehbeeinträchtigung?

☐ Ja ☐ Nein

Wenn ja, welche?(optional)

Dioptrien (optional):

Verwenden Sie eine Sehhilfe?

☐ Nein ☐ Brille ☐ Kontaktlinsen

☐ Andere:

Besitzen Sie 3D-fähige Geräte?

☐ Nein

☐ Ja, ich besitze:

Haben Sie schon einmal einen 3D-Film gesehen?

☐ Nie	
☐ Sehr selten	(nur einmal)
☐ Selten	(nur ein paar Mal)
☐ Hin und wieder	(mehrmals im Jahr)
☐ Oft	(mehrmals im Monat)
☐ Sehr oft	(mehrmals pro Woche)

Haben Sie schon einmal ein 3D-PC- oder Videospiel gespielt?

☐ Nie	
☐ Sehr selten	(nur einmal)
☐ Selten	(nur ein paar Mal)
☐ Hin und wieder	(mehrmals im Jahr)
☐ Oft	(mehrmals im Monat)
☐ Sehr oft	(mehrmals pro Woche)

Bitte wenden!

Haben Sie schon einmal außerhalb dieser beiden Kontexte mit stereoskopischem* 3D zu tun gehabt?

☐ Nie	
☐ Sehr selten	(nur einmal)
☐ Selten	(nur ein paar Mal)
☐ Hin und wieder	(mehrmals im Jahr)
☐ Oft	(mehrmals im Monat)
☐ Sehr oft	(mehrmals pro Woche)

Wenn ja, wie?

Fühlen Sie sich beim Betrachten von stereoskopischen* 3D Inhalten unwohl?

☐ Nie. Ich habe keine Probleme beim Betrachten von stereoskopischen* 3D-Inhalten.
☐ Manchmal. Wie äußert sich das?
☐ Ja, immer. Wie äußert sich das?

**3D-fähige Geräte / stereoskopisches Sehen*:

Menschliche Augen haben einen Abstand zueinander. Dadurch nehmen sie ihre Umwelt aus zwei verschiedenen Perspektiven wahr. Das Gehirn fusioniert die beiden wahrgenommenen Bilder zu einem und schafft dabei einen Tiefeneindruck.

In diesem Fragebogen beziehen sich die Fragen nach stereoskopischem Sehen auf künstlich erzeugte 3D-Bilder. Dabei sorgen 3D-fähige Geräte dafür, dass linkes und rechtes Auge unterschiedliche Bilder sehen und der Betrachter einen 3D-Eindruck erlebt.

- Beispielsweise sorgt in einem 3D-Kino eine spezielle Brille dafür, dass die Bilder für linkes und rechtes Auge entsprechend ankommen.

Vielen Dank für Ihre Teilnahme!

Appendix IV: Comfort Zone of a 3D HUD

The following pictures depict comfortable viewing ranges (for VSDs 2 - 15 m) showing one (cf., Figure 4) or multiple depth layers (cf., Figure 5) on a S3D HUD.

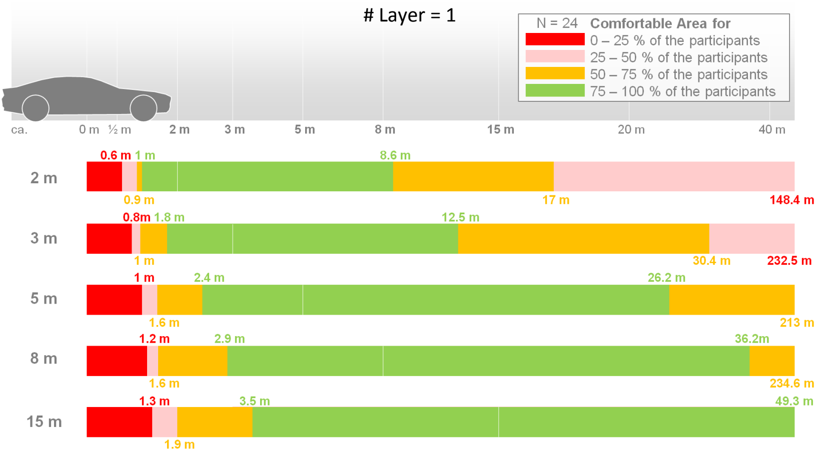


Figure 4: Comfort zone for one depth layer.

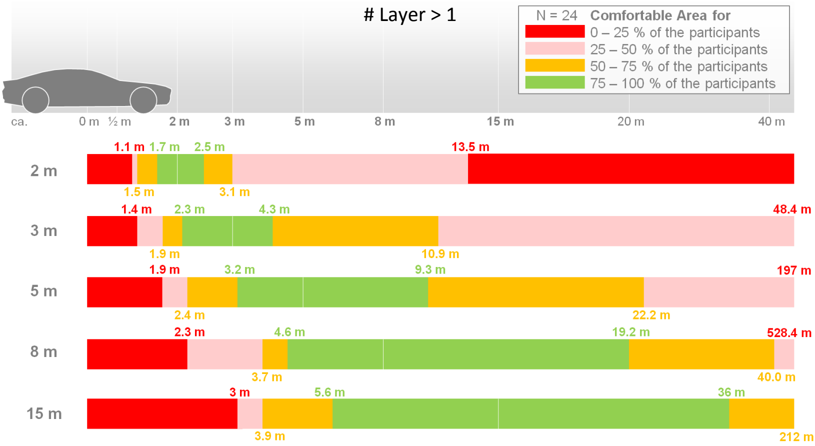
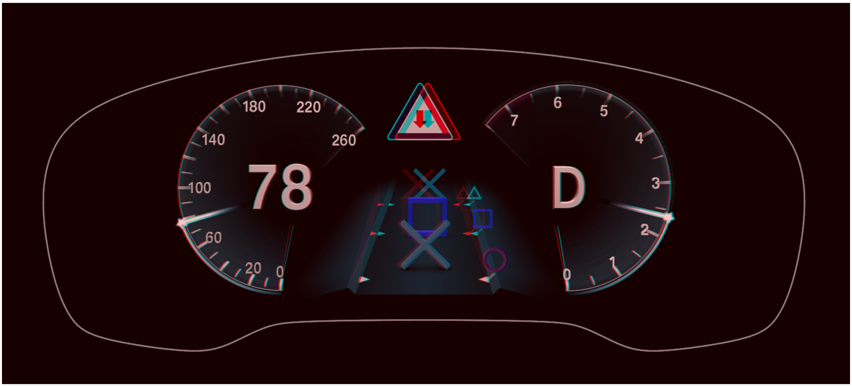
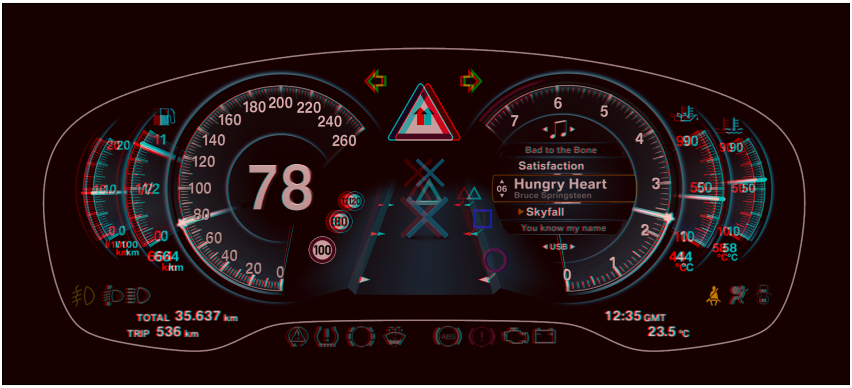


Figure 5: Comfort zone for multiple depth layers.

Appendix V: 3D IC used in the Driving Simulator Study

The following two pictures provide an impression of the used depth layout of the IC used in a simulator study. The upper picture shows a low information load while the picture in the bottom shows the IC with a high information load. These pictures are anaglyph images, which can be viewed using red-cyan glasses. The depicted image size does not correspond to the size of the display used in the study. As a result of the anaglyph decoding and the reduced image size, the 3D quality of the shown images is considerably worse compared to the used 3D prototypes in the study.





Appendix VI: Test Vehicle

We equipped a BMW 5 series with an autostereoscopic display as IC. The display was placed at an angle of 80° to the ground. The viewing distance depends on the driver's size and hence varies between 60 and 90 cm. The Figure 6 illustrates the construction data.

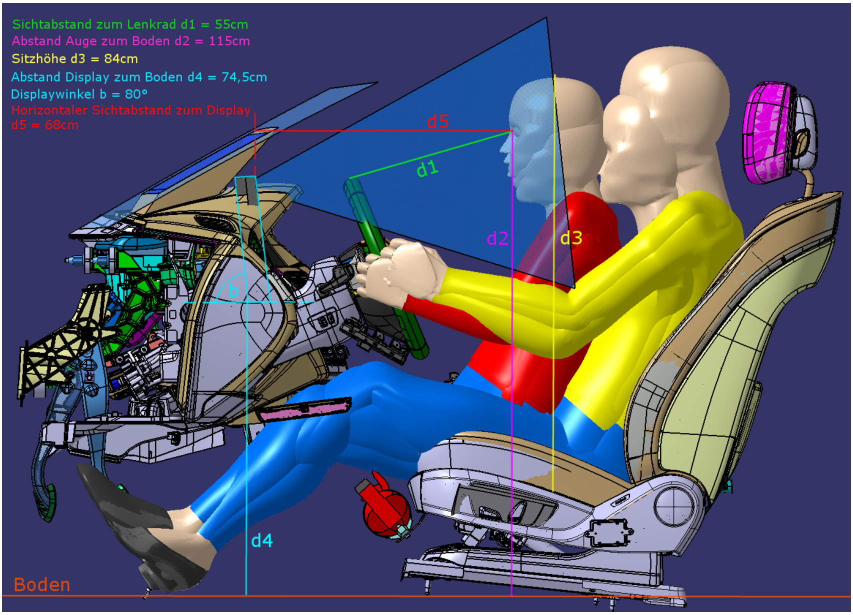


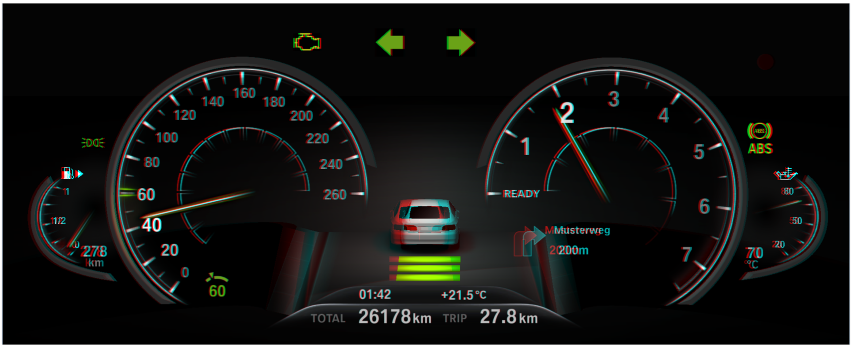
Figure 6: Construction data of the test vehicle.

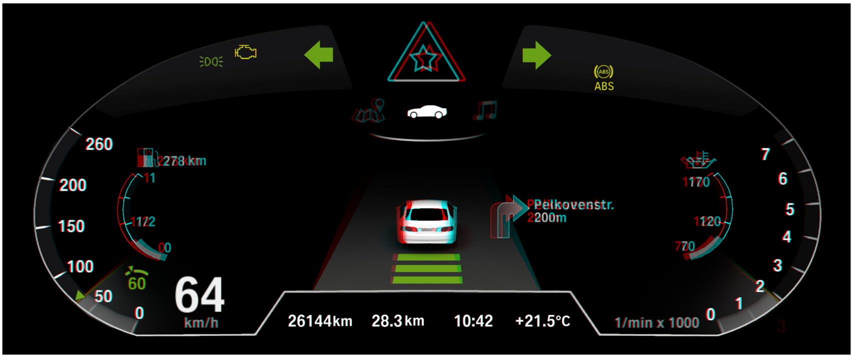
Figure 7 demonstrates the appearance of the integrated display from two perspectives. The upper picture depicts the perspective of the driver on the instrument cluster.

Figure 7: Two perspectives on the integrated 3D display.

Appendix VII: 3D ICs used in the Real-World Study

The following two pictures provide an impression of the used S3D IC concepts for our real-world studies. The upper picture shows the initial concept which was evaluated by experts in automotive UIs. The picture in the bottom depicts the refined IC concept applied for the second study with non-expert. These two pictures are anaglyph images, which can be viewed using red-cyan glasses. The depicted image size does not correspond to the size of the display used in the study. As a result of the anaglyph decoding and the reduced image size, the 3D quality of the shown images is considerably worse compared to the used S3D prototypes in our studies.





Appendix VIII: Study Instructions for the Real-World Study

We conducted the expert study based on the following document:

---------------------------------- Vorbereitung ----------------------------------

Einführung

Danke für die Teilnahme an diesem Versuch.
Es geht um **die Bewertung eines 3D Displays** zur **Anzeige eines Kombiinstruments**.
Dazu haben wir ein 3D Display in dieses Auto integriert, dass zwar **nicht automotivefähig** ist und den qualitativen Ansprüchen hinsichtlich Auflösung noch nicht genügt, aber schon einen guten ersten Eindruck liefert wie sich ein in 3D dargestelltes UI im Fahrzeug anfühlt.
Da dies ein prototypischer Aufbau ist müssen wir zunächst in die **Benutzung des Fahrzeugs einweisen** und Ihnen die **sicherheitskritischen Eigenschaften** des Systems **aufzeigen**:

- Bitte stellen Sie sicher, dass das **Head-Up Display** gut eingesehen werden kann (Anzeige im Head-Up Display ist maßgebend)!

- **Ablenkung des Fahrers** durch Ausfall von Anzeigen oder durch Benutzung der Systeme (Blickerfassung und 3D-Anzeigen).

- Bedienung der Simulation nur **mit höchster Vorsicht** und in übersichtlichen Verkehrssituationen.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Bitte bestätigen Sie mit ihrer Unterschrift dass Sie im Besitz eines gültigen Führerscheins der Klasse B und des BMW Führerscheins B1 sind.

FILMHINWEIS
Zwei GoPros sowie Head mounted Camera. Die Videos werden selbstverständlich nicht veröffentlicht und anonymisisert verarbeitet.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Vorstellung des Projekts:

In dieser Studie geht es um die Erprobung von 3D-Displays im Fahralltag hinsichtlich Benutzbarkeit, Ablesbarkeit und Ablenkung. Der Fokus liegt auf der Verwendung eines 3D-Displays als Kombiinstrument und dessen Abschneiden gegenüber einer 2D-Anzeige.
Gefragt ist Ihre Meinung als HMI-Experte

Instruktionen vor der ersten Fahrt:

- *Stereo Vision Test (RDS)*
- *Einführung in das UI: Erklärung Basislayout in der Variante der ersten Versuchsfahrt und dessen Funktionen (ACC, Notifications)*

- Es finden 2 Testfahrten (Dauer einer Fahrt: 20 Minuten) mit jeweils einer Displayvariante statt. Das Kombiinstrument gibt Ihnen die Route vor durch Einblendungen von Navigationshinweisen
- Neben den Navigationshinweisen treten noch weitere Notifications während der Fahrt auf. Bitte reagieren Sie auf alle Notifications wie folgt:
    - Notification so schnell wie möglich bestätigen durch Druck der markierten Taste am Lenkrad
    - Dem Versuchsleiter den Inhalt der Notification mitteilen (Tank, Navigation, Speed Limit)
- *Üben der Nebenaufgabe im Stand*
- *Starten der Versuchsfahrt falls der Proband alles verstanden und keine Fragen mehr hat.*
- Bitte starten Sie nun die zweite Fahrt. Folgen Sie dabei den Navigationshinweisen im Kombiinstrument und bestätigen Sie so schnell wie möglich auftretende Notifications. Fokussieren Sie sich bitte auf die Fahraufgabe und beachten Sie zu jeder Zeit die Verkehrsregeln. Falls die Verkehrssituation eine Bearbeitung der Aufgaben nicht erlaubt, ignorieren Sie die Aufgaben im Kombiinstrument. Falls Sie sich unwohl fühlen geben sie uns bitte Bescheid. Wir können den Versuch jederzeit abbrechen.

---------------------------------- Versuchsfahrt ----------------------------------

Notizen zu Beobachtungen und Probandenaussagen während der Fahrt

---------------------------------- Fragebögen & Interviews ----------------------------------

Bitte füllen Sie die folgenden zwei Fragebögen hinsichtlich der Interaktion mit dem Kombiinstruments während der gerade erlebten Fahrt aus.

Aushändigen des Mini AttrakDiffs und DALI

Semistrukturiertes Interview:

Allgemein

- Wie haben sie die letzte Fahrt erlebt (im Bezug auf die Interaktion mit dem Kombiinstrument)?

- Wie gut bewerten Sie die **Ablesbarkeit** der **permanenten Anzeige**?
  (Positiv/Negativ? Praktisch? Verwirrend? Anstrengend?)

- Wie war der **Blickwechsel** zwischen dem Display und der Straße? *(Leicht/Schwer? Länger gebraucht um zu Akkommodieren?)*

- Haben Sie den Eindruck, die Darstellung der Instrumente hat Ihr **Blickverhalten** beeinflusst? Mussten Sie öfter oder länger auf das Display schauen um die gewünschten Inforamtionen abzulesen?

- Wurden Sie von der Fahraufgabe durch die Darstellung im Kombiinstrument abgelenkt?

Sonderfunktionen:

- *Was halten Sie von der Einbettung der **Navigation**? Warum?*
  (zu auffällig/unauffällig?   richtig positioniert? [Alternativen?])

- *Was halten Sie von der Anzeige des **Tempolimits**? Warum?*

- *Was halten Sie von der Warnung über den zu niedrigen **Tankfüllstand**? Warum?*

- *„Wie bewerten Sie die Anzeige beim Einstellen des **ACC/Tempomat**?“*

---------------------------------- Vorbereitung der 2. Fahrt ----------------------------------

- *Präsentation des UI in der zweiten Anzeigevariante(Basislayout, ACC, Notifications)*
- Sehen Sie einen **Unterschied zu der vorherigen Variante**? Wenn ja wie würden Sie diesen beschreiben?
- *Üben der Nebenaufgaben im Stand*
- *Starten der Versuchsfahrt falls der Proband alles verstanden und keine Fragen mehr hat.*
- Bitte starten Sie nun die zweite Fahrt. Folgen Sie dabei den Navigationshinweisen im Kombiinstrument und bestätigen Sie so schnell wie möglich auftretende Notifications. Fokussieren Sie sich bitte auf die Fahraufgabe und beachten Sie zu jeder Zeit die Verkehrsregeln. Falls die Verkehrssituation eine Bearbeitung der Aufgaben nicht erlaubt, ignorieren Sie die Aufgaben im Kombiinstrument. Falls Sie sich unwohl fühlen geben Sie uns bitte Bescheid. Wir können den Versuch jederzeit abbrechen.

Wiederholen des Ablaufs „Versuchsfahrt“ und „Fragebögen & Interviews“

---------------------------------- Abschlußinterview ----------------------------------

Allgemeine Fragen

- Was ist ihr Eindruck zu den beiden Fahrten?

- Können Sie sich vorstellen, eine **3D Darstellung** wie die hier gezeigte zu **verwenden**?

- **Welche** Darstellung (2D/3D) hat Ihnen besser gefallen? Warum?

- Wo sehen Sie grundsätzlich **Probleme**, die mit der 3D Darstellung einhergehen könnten?

Strukturierung der Informationen

- Wie stark ist die **Strukturierung** der Ebenen in der 3D Variante **aufgefallen**?
  (→ ggf. Struktur erklären)

  Notieren: Hat der Proband die Strukturierung bemerkt? Auf Anhieb verstanden?

- Finden Sie die **Strukturierung sinnvoll**? Würden Sie manche Elemente anders visualisieren? Was für Möglichkeiten gäbe es noch, die Elemente zu gruppieren? Würden Sie die Tiefenstruktur ändern? Wie?

- Halten Sie das **Highlighting mittels 3D** von dringenden Informationen für **sinnvoll**? *(Verständlich? Überladen?)*

Varianten der Tiefenstruktur:

Präsentation der 4 Varianten

1. *PopUp auf Screenebene, Tuben auf Screenebene*
2. *PopUp auf Screenebene, Tuben hinter Screenebene*
3. *PopUp vor Screenebene, Tuben auf Screenebene*
4. *PopUp vor Screenebene, Tuben hinter Screenebene*

Erkennen Sie einen Unterschied zwischen den Varianten? Welchen?

➔ *Hat der Proband einen Unterschied bemerkt? Eine Vorliebe? Warum?*
(mitloggen, ob der Proband verstanden hat, worum es geht und wie gut)

Varianten der ACC Darstellung:

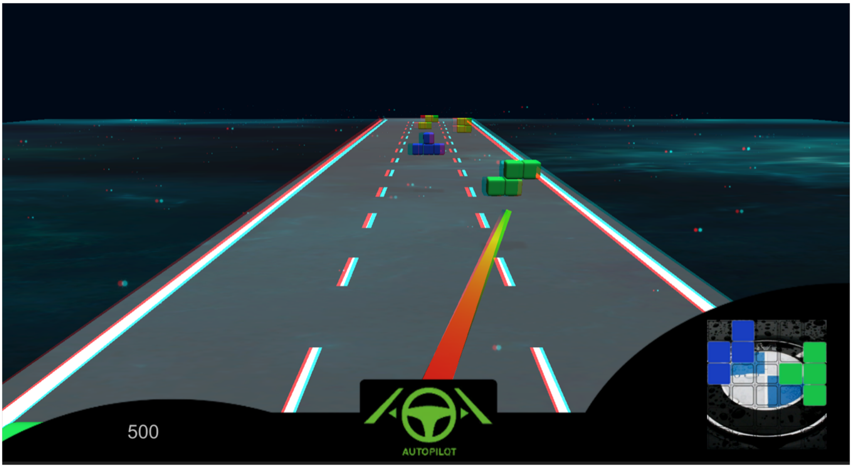
Präsentation der 2 Varianten: Perspektivisch und Vogelperspektive

Welche Variante gefällt Ihnen besser? Warum?

Erfassung demographischer Daten und verabschieden des Probanden mit kleiner Belohnung

Appendix IX: Space Tetris 3D

The following picture provides an impression of the S3D game Space Tetris. Our study participants played the game while highly automated driving in a driving simulator. The picture is an anaglyph image, which can be viewed using red-cyan glasses. The depicted image size does not correspond to the size of the display used in the study. As a result of the anaglyph decoding and the reduced image size, the 3D quality of the shown image is considerably worse compared to the used S3D prototype in our study.



Nora Broy

Stereoscopic 3D User Interfaces

Exploring the Potentials and Risks of 3D Displays in Cars

During recent years, rapid advancements in stereoscopic digital display technology has led to acceptance of high-quality 3D in the entertainment sector and even created enthusiasm towards the technology. The advent of autostereoscopic displays (i.e., glasses-free 3D) allows for introducing 3D technology into other application domains, including but not limited to mobile devices, public displays, and automotive user interfaces – the latter of which is at the focus of this work. Prior research demonstrates that 3D improves the visualization of complex structures and augments virtual environments. We envision its use to enhance the in-car user interface by structuring the presented information via depth. Thus, content that requires attention can be shown close to the user and distances, for example to other traffic participants, gain a direct mapping in 3D space.

The core question of this thesis is whether and how stereoscopic 3D can contribute to advanced automotive user interfaces. Through laboratory, driving simulator, and real world driving studies potentials and risks of in-car 3D displays are explored. The results of this thesis should motivate future research and support practitioners in developing innovative 3D technologies and applications inside as well as outside the car.