The Cockpit for the 21st Century

Exploring large and shaped interactive surfaces for direct interaction

Dissertation

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Sonja Rümelin

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Erstgutachter: Prof. Dr. Andreas Butz
Zweitgutachter: Prof. Dr. Antonio Krüger

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Die Welt ist gräßlich – und wunderschön!

– Gisbert zu Knyphausen –

ABSTRACT

Interactive surfaces are a growing trend in many domains. As one possible manifestation of Mark Weiser's vision of ubiquitous and disappearing computers in everywhere objects, we see touch-sensitive screens in many kinds of devices, such as smartphones, tablet computers and interactive tabletops. More advanced concepts of these have been an active research topic for many years. This has also influenced automotive cockpit development: concept cars and recent market releases show integrated touchscreens, growing in size. To meet the increasing information and interaction needs, interactive surfaces offer context-dependent functionality in combination with a direct input paradigm.

However, interfaces in the car need to be operable while driving. Distraction, especially visual distraction from the driving task, can lead to critical situations if the sum of attentional demand emerging from both primary and secondary task overextends the available resources. So far, a touchscreen requires a lot of visual attention since its flat surface does not provide any haptic feedback. There have been approaches to make direct touch interaction accessible while driving for simple tasks. Outside the automotive domain, for example in office environments, concepts for sophisticated handling of large displays have already been introduced. Moreover, technological advances lead to new characteristics for interactive surfaces by enabling arbitrary surface shapes.

In cars, two main characteristics for upcoming interactive surfaces are *largeness* and *shape*. On the one hand, spatial extension is not only increasing through larger displays, but also by taking objects in the surrounding into account for interaction. On the other hand, the flatness inherent in current screens can be overcome by upcoming technologies, and interactive surfaces can therefore provide haptically distinguishable surfaces. This thesis describes the systematic exploration of large and shaped interactive surfaces and analyzes their potential for interaction while driving. Therefore, different prototypes for each characteristic have been developed and evaluated in test settings suitable for their maturity level. Those prototypes were used to obtain subjective user feedback and objective data, to investigate effects on driving and glance behavior as well as usability and user experience.

As a contribution, this thesis provides an analysis of the development of interactive surfaces in the car. Two characteristics, *largeness* and *shape*, are identified that can improve the interaction compared to conventional touchscreens. The presented studies show that large interactive surfaces can provide new and improved ways of interaction both in driver-only and driver-passenger situations. Furthermore, studies indicate a positive effect on visual distraction when additional static haptic feedback is provided by shaped interactive surfaces. Overall, various, non-exclusively applicable, interaction concepts prove the potential of interactive surfaces for the use in automotive cockpits, which is expected to be beneficial also in further environments where visual attention needs to be focused on additional tasks.

ZUSAMMENFASSUNG

Der Einsatz von interaktiven Oberflächen weitet sich mehr und mehr auf die unterschiedlichsten Lebensbereiche aus. Damit sind sie eine mögliche Ausprägung von Mark Weisers Vision der allgegenwärtigen Computer, die aus unserer direkten Wahrnehmung verschwinden. Bei einer Vielzahl von technischen Geräten des täglichen Lebens, wie Smartphones, Tablets oder interaktiven Tischen, sind berührungsempfindliche Oberflächen bereits heute in Benutzung. Schon seit vielen Jahren arbeiten Forscher an einer Weiterentwicklung der Technik, um ihre Vorteile auch in anderen Bereichen, wie beispielsweise der Interaktion zwischen Mensch und Automobil, nutzbar zu machen. Und das mit Erfolg: Interaktive Benutzeroberflächen werden mittlerweile serienmäßig in vielen Fahrzeugen eingesetzt. Der Einbau von immer größeren, in das Cockpit integrierten Touchscreens in Konzeptfahrzeuge zeigt, dass sich diese Entwicklung weiter in vollem Gange befindet. Interaktive Oberflächen ermöglichen das flexible Anzeigen von kontextsensitiven Inhalten und machen eine direkte Interaktion mit den Bildschirminhalten möglich. Auf diese Weise erfüllen sie die sich wandelnden Informations- und Interaktionsbedürfnisse in besonderem Maße.

Beim Einsatz von Bedienschnittstellen im Fahrzeug ist die gefahrlose Benutzbarkeit während der Fahrt von besonderer Bedeutung. Insbesondere visuelle Ablenkung von der Fahraufgabe kann zu kritischen Situationen führen, wenn Primär- und Sekundäraufgaben mehr als die insgesamt verfügbare Aufmerksamkeit des Fahrers beanspruchen. Herkömmliche Touchscreens stellen dem Fahrer bisher lediglich eine flache Oberfläche bereit, die keinerlei haptische Rückmeldung bietet, weshalb deren Bedienung besonders viel visuelle Aufmerksamkeit erfordert. Verschiedene Ansätze ermöglichen dem Fahrer, direkte Touchinteraktion für einfache Aufgaben während der Fahrt zu nutzen. Außerhalb der Automobilindustrie, zum Beispiel für Büroarbeitsplätze, wurden bereits verschiedene Konzepte für eine komplexere Bedienung großer Bildschirme vorgestellt. Darüber hinaus führt der technologische Fortschritt zu neuen möglichen Ausprägungen interaktiver Oberflächen und erlaubt, diese beliebig zu formen.

Für die nächste Generation von interaktiven Oberflächen im Fahrzeug wird vor allem an der Modifikation der Kategorien *Größe* und *Form* gearbeitet. Die Bedienschnittstelle wird nicht nur durch größere Bildschirme erweitert, sondern auch dadurch, dass Objekte wie Dekorleisten in die Interaktion einbezogen werden können. Andererseits heben aktuelle Technologieentwicklungen die Restriktion auf flache Oberflächen auf, so dass Touchscreens künftig ertastbare Strukturen aufweisen können. Diese Dissertation beschreibt die systematische Untersuchung großer und nicht-flacher interaktiver Oberflächen und analysiert ihr Potential für die Interaktion während der Fahrt. Dazu wurden für jede Charakteristik verschiedene Prototypen entwickelt und in Testumgebungen entsprechend ihres Reifegrads evaluiert. Auf diese Weise konnten subjektives Nutzerfeedback und objektive Daten erhoben, und die Effekte auf Fahr- und Blickverhalten sowie Nutzbarkeit untersucht werden.

Diese Dissertation leistet den Beitrag einer Analyse der Entwicklung von interaktiven Oberflächen im Automobilbereich. Weiterhin werden die Aspekte *Größe* und *Form* untersucht, um mit ihrer Hilfe die Interaktion im Vergleich zu herkömmlichen Touchscreens zu verbessern. Die durchgeführten Studien belegen, dass große Flächen neue und verbesserte Bedienmöglichkeiten bieten können. Außerdem zeigt sich ein positiver Effekt auf die visuelle Ablenkung, wenn zusätzliches statisches, haptisches Feedback durch nicht-flache Oberflächen bereitgestellt wird. Zusammenfassend zeigen verschiedene, untereinander kombinierbare Interaktionskonzepte das Potential interaktiver Oberflächen für den automotiven Einsatz. Zudem können die Ergebnisse auch in anderen Bereichen Anwendung finden, in denen visuelle Aufmerksamkeit für andere Aufgaben benötigt wird.

PREFACE

This thesis is the result of the time I spent in the team for Mensch-Maschine-Interaktion at BMW Forschung und Technik from 2011 - 2013. During this period, I did not work in isolation, but all of my decisions were strongly influenced by innumerable conversations and discussions with my team colleagues. In addition to that, the exchange with researchers, in particular from the Human-Computer Interaction and Media Informatics groups of the LMU, but also at occasions such as the conferences I visited, was very valuable and inspiring.

To emphasize that all those cooperations significantly contributed to the making of this thesis, I decided to use the scientific plural. Additionally, the publications which the sections describing the concepts and prototypes are based on, are highlighted at the beginning of the respective sections. To allow for a consistent presentation throughout this thesis, the content from those publications has been restructured and complemented with additional information if necessary.

ACKNOWLEDGMENTS

The last three years were filled with ups and downs, but all the time, a lot of people have contributed to let the good times prevail. I want to thank you all for your support and patience!

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I want to thank all my colleagues at BMW Forschung und Technik. **Christopher Rölle**, who made it possible to (almost) finish within three years and who finally, somehow, valued my DIY-style prototype. I learned a lot in those three years! Further thanks goes to **Max Graf** for being such a "lockerer Typ", **Felix Lauber** for the moments he appeared behind my screen, **Martin Knobel** for making me apply for the PhD position, **Melanie Lamara** for her help with statistics, **Wilfried Hajek**, **Nora Broy**, and **Philipp Kerschbaum**. My thanks also goes to **Ralf Decke**, **Manja Just**, **Stefan Kaindl**, **Josef Schumann**, **Lenja Sorokin** and **Wolfgang Spießl** - I had inspiring office hours and coffee breaks with you and the rest of the team! In particular, I want to thank **Bernhard Niedermaier** and **Ronee Chadowitz** for being great team leaders who gave me a lot of freedom, but also support and advice.

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TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

List of Acronyms

AAM	Alliance of Automobile Manufacturers
AC	air conditioning
AR	augmented reality
AR	anti-reflectance
ANOVA	analysis of variance
ATM	automated teller machine
BMW	Bayerische Motorenwerke
CAN	controller area network
CE	consumer electronics
CID	central information display
CRT	cathode ray tube
DALI	Driving Activity Load Index
DI	diffuse illumination
DLP	digital light processing
DMD	digital mirroring device
EADS	European Aeronautic Defence and Space Company
ESOP	European statement of principles
FOLED	flexible OLED
FBM	functional bookmark
FTIR	frustrated total internal reflection
GIS	Geoinformation system
GUI	graphical user interface
HCI	human-computer interaction
HDD	head-down display
HMD	head-mounted display
HQ	hedonic quality
HUD	head-up display
IC	instrument cluster

IR	infra red
ISO	International Organization for Standardization
IVIS	in-vehicle information system
LBS	location-based service
LCD	Liquid Crystal Display
LCoS	Liquid Crystal on Silicon
LCT	Lane Change Task
LED	light emitting diode
MEMS	microelectromechanical system
NHTSA	National Highway Traffic Safety Administration
ODICIS	One Display for a Cockpit Interactive Solution
OLED	Organic light emitting diode
OUI	organic user interface
PanDis	Panoramic Displays
PC	personal computer
PDT	peripheral detection task
PID	passenger information display
PND	personal navigation device
POI	point of interest
PQ	pragmatic quality
RTF	remote tactile feedback
SMA	shape memory alloy
SUS	System Usability Scale
TFT	thin film transistor
TLX	Task Load Index
TOF	time-of-flight
TTC	time to collision
TTS	text-to-speech
TUI	tangible user interface
UI	user interface
USA	United States of America
VR	virtual reality
WIMP	Window, Icon, Menu, Pointer

Chapter 1

Introduction

In his article "The Computer for the 21st Century" from 1991, Mark Weiser presented his vision that technologies will one day disappear, and that computers will be indistinguishable from everyday objects, thus integrating seamlessly to their environment [302]. As computers are the integral part of automotive infotainment systems, I would like to bring his concept into the context of the car, and provide a vision of what the *cockpit* for the twenty-first century could look like.

Humans should be able to adjust the type of access they have to information depending on the current context. In an office environment, Weiser suggests the use of differently sized devices – "tabs, pads, and boards" [302] – for different situations. This leads us to the idea to also provide an appropriate access in the specific context of a car. In the recent decades, more and more controls and screens have been gradually added to the cockpit, by placing them at positions reasonable from a construction or ergonomic point of view. Weaving the platform into the existing environment, however, would require a more seamless integration. By building interfaces based on *interactive surfaces*, we can enhance the existing surfaces of objects. We can make the objects themselves interactive and use them to interact with the digital world. Therefore, interactive surfaces will form the basis of this work.

Keeping in mind the automotive context, this thesis aims to explore different aspects of interactive surfaces, with regard to their potential for interaction, and their contribution to increasing the feasibility of secondary interaction while driving.

1.1 Motivation

People are spending a lot of time "on the go". Even in conservative estimations, motorized individual traffic will still take a 75% share of transportation modes in the upcoming decade [69]. This relates to an average distance of about 39 km by car every day per person in Germany [297]. At the same time, the interaction with "the digital world" is growing – people are spending hours in social networks, gathering information from the web, or keeping themselves up to date with the latest news [25]. Consequently, travel time is often used for accomplishing tasks other than operating the car. Listening to news, making phone calls, texting (often performed via mobile phones [8]) or getting information on train departure times; there is a variety of information that people might currently want to access in the car. Car manufacturers have adjusted accordingly and offer infotainment systems which include a wide range of functionality, accessible via a cockpit architecture that features screens and multifunctional controllers. A recent trend is to integrate mobile devices in the car via so called "terminal modes" [29] that allow applications to run on integrated screens and and to be operated via the integrated controls. This development is especially encouraged by consumer electronics (CE) companies such as Apple[1].

On the other hand, statistics have shown that the crash increases when secondary tasks cause visual distraction [153]. In particular, interacting with mobile phones, for example texting while driving [26], leads to a larger decrease of driving safety than interacting with the integrated devices does [193]. Keeping the driver's interaction space within the integrated car controls, and ensuring that the driver's attention is kept on the traffic situation, is therefore the main target to meet when developing automotive interfaces. Input devices need to be designed to be in direct reach and accessible without diverting visual attention from the road, while (visual) output devices need to be legible while driving (in direct sun light, regarding text sizes etc.).

Besides the changing and restrictive requirements for infotainment systems, interaction habits are evolving. As a result, concepts for displaying and controlling content on automotive user interfaces have evolved over time. Simple buttons and knobs in the early days of in-car entertainment have been replaced by complex systems, such as BMW iDrive, Daimler COMAND or Audi MMI. Those systems allow access to a multitude of functions, yet, they require indirect interaction through a remote control. Only recently have car manufacturers started to follow the CE trend to integrate touchscreens into their products. They offer direct manipulation of on-screen objects as well as a flexible interface design. However, they lack haptic feedback due to their flat surface. Given the technological development of large and freely formable displays, we can look for new interface strategies to **compensate** for the deficient haptic feedback of touchscreens.

[1] Mat Smith: Apple announces CarPlay: in-vehicle voice and touch access to notifications, maps and music. `http://www.engadget.com/2014/03/03/apple-announces-carplay-voice-and-touch-access-offers-access-to/` [cited 2014-03-03]

1.2 Objectives

Based on the recognized problems with touchscreens in the car, we state two main research questions as specified below. By answering those, our contributions aim to support the design of user interfaces for large and shaped interactive surfaces (see Figure 1.1).

1.2.1 Problem statement

For the design of automotive user interfaces, various aspects have to be taken into account. Besides the satisfaction of information and interaction needs, it is most important to ensure safety for drivers and passengers. So far, automated driving has only reached the market with features such as lateral and longitudinal assistance. Therefore, the main task for the driver remains to control the vehicle. As a result, car manufacturers and other content and control providers need to ensure that secondary interaction does not distract the driver from this task.

Interactive surfaces have the potential to fulfill both information and interaction needs, by offering a platform to access content and functionality directly, either provided by an in-car system or a brought-along device. However, interactive surfaces we are using today – flat touch-sensitive screens in varying sizes – have their disadvantages. They do not offer any haptic orientation and require visual attention to locate the interactive elements that are displayed. This stands in sharp contrast to the key requirement that the driver needs to observe the road scene at all times, in order to react to unexpected events. The goal of this thesis is to provide interfaces that hold the visual attention, which is required for secondary interaction, within a reasonable range.

Therefore, we need to identify **alternative ways to control** interactive surfaces. Secondary interaction while driving is only one example for a use case where visual distraction has to be kept low. We may want to control our smartphone while walking [202], or we may not be able to look at a device because we are engaged in an observational primary task [243]. Potential solutions might be provided by physical characteristics of interactive surfaces. Due to technological advances, interactive surfaces have already grown in size and will soon also lose the limitation of being flat. As a result, this thesis will focus on the development of concepts for large and shaped interactive surfaces.

1.2.2 Research questions

This thesis aims to answer the following research questions:

> **RQ1: How does the interaction with large and shaped interactive surfaces affect visual attention while driving?**

Early automotive user interfaces were based on buttons and switches. Physical control elements can be localized blindly since their shape can be recognized through touch. Furthermore, they provide feedback which we can feel when we push or turn them. Increasingly, these systems are being replaced by touchscreen-based solutions. They often consist of medium-sized screens which are mounted to the center stack. The challenge that arises for the design of direct touch interfaces is that they lack feedback and do not support the haptic perception that eases the interaction with physical controls. As a result, they require visual attention and thus violate a main requirement of interaction while driving. RQ1 aims to answer how automotive user interfaces on interactive surfaces can be designed to satisfy this requirement. To investigate the suitability while driving, we will evaluate our prototypes with a focus on visual distraction.

Methodology:
Review of related work, expert workshops, realization and evaluation of prototypes.

RQ2: How can interactive surfaces be designed to reduce visual distraction?

We tend to perform several tasks at a time; however, human resources for information processing are limited. Therefore, we need to efficiently share them between different tasks. If the primary task asks for most of the visual attention, the additional tasks have to be performed using the remaining capacities. As a result of our evaluations, we aim to derive general recommendations for the design of user interfaces on interactive surfaces. Their physical properties *largeness* and *shape* provide the potential to reduce the need for visual attention by replacing or complementing it with haptic perception.

Methodology:
Analysis of direct interaction, consolidation of study results, derivation of recommendations.

1.3 Contributions

Resulting from the theoretic and practical work presented in this thesis, several contributions to the field of interaction on interactive surfaces are provided. Those are discussed in detail in Section 6.1.

1.3.1 Realizations of prototypical interfaces

This thesis begins by describing the design and technical implementation of several prototypes realizing automotive user interfaces on large and shaped interactive surfaces. On the one side, this can inspire researchers to further explore the interactive space which future cockpits or other environments may offer. On the other side, we present the technical approaches we used to build prototypes of shaped interactive surfaces with different levels of fidelity. This allows the recreation and further extension of the concepts presented.

1.3.2 Insights into the effect on visual distraction

Evaluating our exemplary prototypes, we investigate the effects of *largeness* and *shape* on usability and primary task performance. Even more important, we give valuable insights into their effect on visual distraction. Based on related work, we classify different phases of direct touch input and specify how those rely on visual attention. In several user studies, we evaluate how our concepts affect visual attention in the separate interaction steps to answer RQ1.

1.3.3 Guidelines for the direct interaction with interactive surfaces

Lastly, we sum up the experiences we gained in the evaluations to derive design guidelines on how to make best use of large and shaped interactive surfaces (RQ2). Analyzing visual distraction in the different phases of interaction, we summarize how the properties *largeness* and *shape* can be used to reduce visual distraction. As a contribution, we provide several concrete recommendations on how the steps of direct interaction can be improved. This is achieved by strengthening the haptic perception based on the physical properties *largeness* and *shape*. Both the tactile and the kinesthetic part of haptic perception can be increasingly integrated into the interaction so that visual attention can be focused on critical primary tasks.

1.4 Thesis structure

After this introduction, the remaining chapters of this thesis are organized as follows:

- *Chapter 2 – Background* provides an overview of the automotive context and the requirements it sets for the user interface design (Section 2.1). It presents different directions of research on automotive user interfaces and substantiates the choice of this thesis to engage with interactive surfaces. Furthermore, it introduces the field of interactive surfaces, its application areas and background information on technical solutions (Section 2.2).
- *Chapter 3 – The Next-Generation Cockpit? Large and Shaped Interactive Surfaces in the Car* summarizes how automotive user interfaces have already started to integrate interactive surfaces and gives indications on how this development might continue (Section 3.1). It describes the design space for the development of interactive systems, analyzes the interaction phases for direct interaction, and defines the thesis' boundaries within this space (Section 3.2). Based on this, it extends the discussion of related work with regard to the interaction on large and shaped interactive surfaces (Section 3.3 and 3.4). The chapter closes with a summary of potential benefits (Section 3.5).

- *Chapter 4 – Large Interactive Surfaces* describes the first set of prototypes with a focus on *large* interactive surfaces. It is structured according to passenger situations and cockpit configurations (Section 4.1). For each prototype, it describes the concept and its evaluation, closing with a discussion on the results (Section 4.2 - 4.4). Finally, it summarizes the presented results according to the phases of direct interaction (Section 4.5).
- *Chapter 5 – Shaped Interactive Surfaces* describes the second set of prototypes which were developed to explore the use of *shaped* interactive surfaces. First, it describes some preliminary considerations based on expert interviews (Section 5.1). After a basic experiment, prototypes are grouped by their underlying basic shape (Section 5.2 - 5.4). Again, each prototype is described in detail, followed by a discussion of the evaluation. The chapter closes with a summary of the results (Section 5.5).
- *Chapter 6 – Conclusion and Future Work* closes the dissertation. It summarizes the contributions and highlights directions for future work.

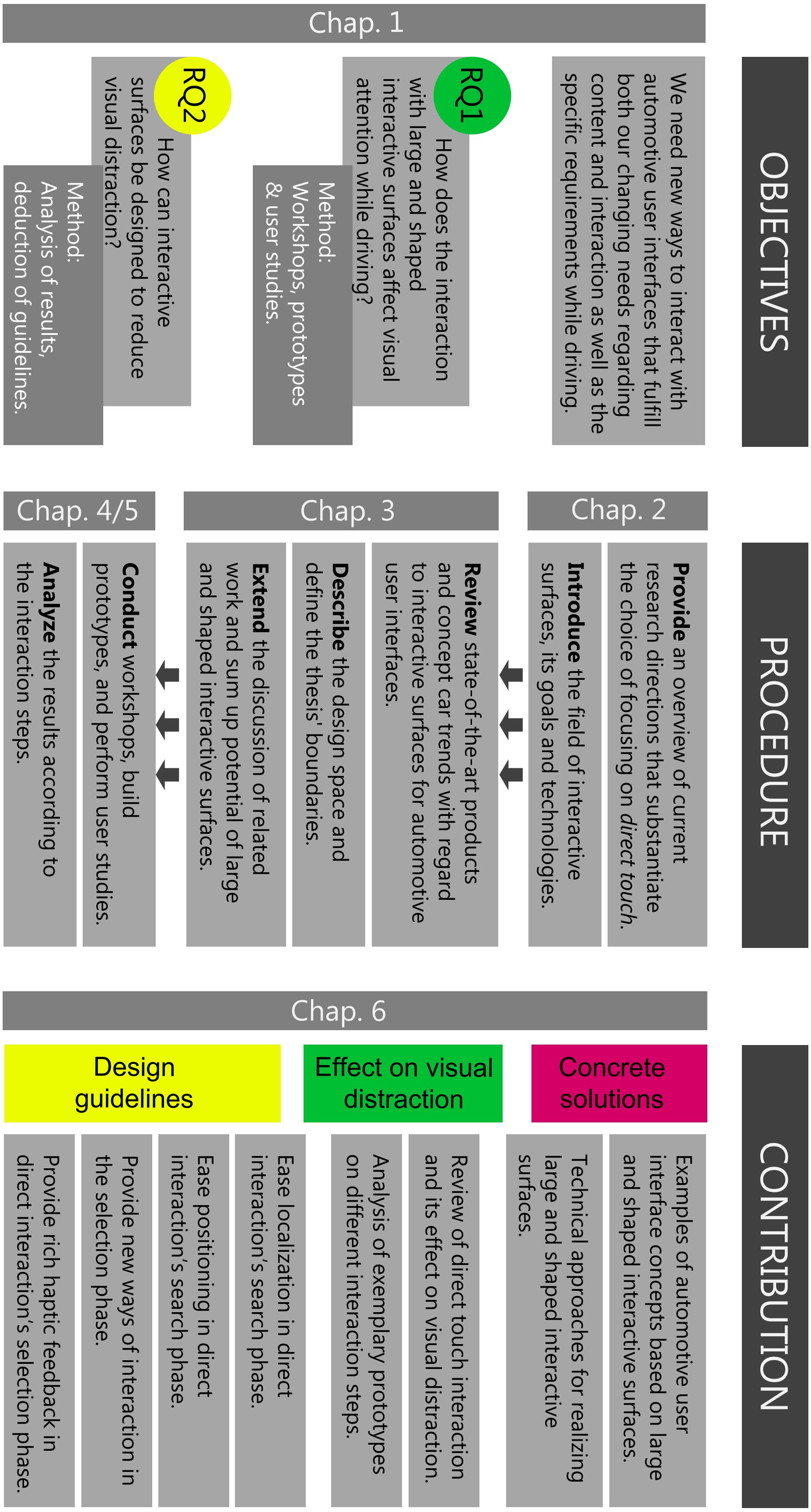

Figure 1.1: Summary of the thesis' approach and contributions.

Chapter 2

Background

When thinking about how future cockpits can be controlled if large and shaped interactive surfaces are integrated, the first step in this thesis will be to provide an overview of the field of automotive interaction as well as the field of interactive surfaces. What are the specific conditions in the car? What do people want to control? And what are current fields of research? What are interactive surfaces, in which domains do we use them today, and how can they be technically realized? This is the basis for the further considerations in the subsequent chapters.

2.1 Automotive interaction

Designing interaction for a cockpit requires to take into account the driving context and the interactions that take place during driving, now and in the future. There are specific requirements and regulations for the automotive context that need to be fulfilled in comparison to other mobile or stationary contexts. Moreover there are specific requirements and behavioral habits of users inside the car.

Different observational studies have investigated tasks and patterns while driving and they highlight the interaction need apparent in the car. On the other side, there is the obvious need to lower distraction and the input of recommendations and standards that restrict the free access to information, entertainment and communication services. Research in industry and academia follows different approaches to cope with this trade-off. One of those is to take the advantages of direct touch and solve existing challenges with new interaction concepts.

2.1.1 Automotive context

We do not only drive when we drive. Besides steering, accelerating and braking, we activate indicators and wipers, but also control entertainment and information devices. Moreover, we might have passengers, eat, smoke or reach for something on the passenger seat. The car offers functionality for the first categories. Bubb [35] classify manoeuvring tasks as primary, additional mandatory tasks as secondary, and further additional interactions as tertiary. When designing automotive user interfaces, it is especially important to ensure that driving can be performed safely despite a growing amount of tertiary functionality. More generally, secondary tasks have also been defined to be "tasks that are not necessay to the primary task of driving" [89]. An important term in this context is *infotainment*, which is made up from the words *information* and *entertainment*. Infotainment systems include tertiary functionality as defined by Bubb [35], but also extend to driving assistance systems [185]. While we know very well what these systems offer, we often do not know exactly what customers actually do with them and how they can be optimally supported.

Meschtscherjakov et al. [186] highlight the importance of knowing what is happening, but also the drawbacks of in-car studies that are often used to gather data on customers' behavior. The driver must not be distracted by the observational methods. Additionally, the researcher or any observational device needs to stay in the background as much as possible, as otherwise the behavior of the driver and passengers might be biased. The experimental subjects tend to try out new functions as the study setting triggers their interest in the features of their system and increases their demand to show them off. Contextual inquiries are a way to overcome those problems [186], and will serve to introduce typical habits and demands for people in the car.

Secondary interaction

In 2010, Gellatly et al. [84] presented a field study conducted in the course of a project called *Journey*, which aimed to deepen the understanding of how drivers interact with state-of-the-art infotainment systems. They observed the behavior of users with their system and with brought-along, so called nomadic, devices, as well as the interrelation with the driving task. The inquiry of 30 participants with different backgrounds regarding their type of vehicle as well as driving experience led to five key findings that can inspire future research. First, the car is regarded as *just another location* during their daily life. Participants do not want their activities to be interrupted as soon as the door of the car is closed. As a result, people felt isolated for example when nomadic devices were not supported seamlessly. As a second finding, the study showed that driving was only one task besides many others. Participants were heavily involved in further, *secondary tasks*. Those include traditional infotainment functionality such as communication, navigation, entertainment and vehicle information, but increasingly also online services such as retrieving information on location-based services (LBS) or latest traffic and weather data. The *importance of navigation systems* is a further outcome of the study. They do not only support way-finding, but also improve situation awareness and add to security and entertainment. Moreover, the authors observed that users performed trip planing tasks already in advance of getting into the car. They conclude that navigation systems should also support activities happening beforehand. As a fourth finding, designers of infotainment systems should support the learning process by taking into account their customers' *prior experiences* with technology, as otherwise knowledge gained with CE devices cannot be used and expectations are not met. As their last key finding, the authors stated that customers of luxury brands such as Cadillac or BMW expect their vehicles to provide components clearly distinguishable from lower-class brands. Designing interaction for a luxury car should not just aim for developing functionality, but provide *unique experiences* during and after usage.

With the advent of ubiquitous computing, we interact with our surrounding in a variety of different ways. One possibility to handle this is to adapt interfaces to the context they are used in. Henfridsson and Lindgren [106] observed the behavior of users with communication devices. When switching from pedestrian to driver context, the hand-over should, as pointed out by Gellatly et al., be seamless; however, it is crucial that a *context switch* of the interface *is always communicated* to the user, especially when it is not performed consciously, or when the driver cannot concentrate the attention on the interface. When switching context, one should make use of *context-appropriate controls*. For instance, when switching from pedestrian to driver context, the steering wheel controls that are ensured to be well usable while driving are preferred to the controls of a mobile phone. Furthermore, a common way to integrate functionality in an infotainment system are hierarchical menus. One observation of the study was that different functions, such as "entering a destination" and "making a phone call" are placed at similar levels of the hierarchy; however, the user might have different mental models when performing those tasks. Therefore, it is important to *keep in mind the underlying model* and integrate tasks accordingly at appropriate locations in a menu.

Mobile phones are increasingly brought into the car as nomadic devices. Investigating how people interact with touchscreen devices, Heikkinen et al. [103] found three main categories of tasks that people performed during their car journeys. Those categories were either related to entertainment, such as (mostly passive) interaction with social media and music services, trip-related such as navigation tasks, or work-related, such as reviewing information for a meeting. Participants were creative in reducing the distraction: for example by restricting updates of social media services to specific groups, including only the closest contacts during driving, the number of updates was greatly reduced. Due to the better network connectivity of the mobile devices, most users preferred the mobile devices over the in-car systems. Those were either placed loosely next to the driver, or put into car mounts on the right-hand side of the steering wheel. The loose devices were used by holding the device with one or even both hands while at the same time keeping the hands on the steering wheel to maintain control over the maneuvering task. This, however, resulted in complex situations when this hand had to perform driving-related tasks. Another approach that was applied to cope with the dual-task situation was to postpone certain steps of a task, like the input of text, to less demanding driving situations, and to use mobile versions of applications with interfaces adjusted to low-attention situations, instead of desktop versions. Participants preferred touchscreen gestures instead of precise pointing interaction. Overall, it became clear that *people are aware of the additional workload* induced by the interaction with their mobile device. They tried to minimize visual distraction; however, they did not want to give up using the functionality completely. As a result of their analysis, the author formulate implications on the design of future infotainment systems: they suggest that systems should adapt to the car context, allow for an easy integration of nomadic devices, and create meaningful and consistent interaction models.

In preparation of an experiment comparing different interaction modalities, Harvey et al. [97] developed a set of representative tasks. They looked for tasks that were already available in

Figure 2.1: Observational studies evaluating the automotive context. a: Observer's perspective from the rear seat in contextual inquiries [186]. b: Collaborative navigation [75]. c: Screenshot of video recording of observations of different passenger roles [161]. Details can be found in the text.

current infotainment systems (in 2011), and actually used while driving. The selected tasks were chosen from different domains, such as entertainment, comfort, communication and navigation, and categorized depending on their type of operation. As an example for *discrete selection*, they chose the navigation in a menu with a subsequent item selection. To test *alphanumeric tasks*, entering navigation destination or telephone number were chosen. The third category *level adjustment* was for example represented by adjusting fan speed or bass level.

Driver-passenger interaction

People are driving together in various constellations. They can be friends, colleagues, partners or family members, but also taxi drivers and their customers, or people using a carpool service. Depending on the relationship, the interaction between the different persons in a car differs; however, there are emerging patterns how people interact as well as further interesting episodes and questions that have been reported that might inspire research on automotive interfaces.

Forlizzi and Barley [75] observed the collaborative interaction between driver and fellow passengers when navigating to inform the design of future navigation systems. The participants of the study were divided in pairs of two, one having the role of the driver, the other one the role of the navigator (see Figure 2.1). Depending on the relationship of the pairs and their social roles, the collaboration differed. In terms of providing turn-by-turn information and confirmations, less familiar pairs were more explicit. They concentrated their communication on distances and upcoming maneuvers and remained in their assigned roles. More experienced collaborators tended to provide less detailed but more general instructions. Closely related pairs, such as family members or couples, tended to perform the task more together, for example by discussing route details and prior experiences with it. Landmarks such as street signs helped to coordinate drivers and navigators by providing a reference point. Those landmarks were also used to schedule instructions. They were often provided as soon as a landmark was in sight, independent of the remaining distance to the maneuver. As this might not always be early enough, the pairs did not only rely on navigator-initiated instructions; when the driver felt uncertain about an upcoming maneuver, prompting for information was a common activity. Drivers appreciated the fact that passengers not only gave commands but also helped to look for street signs to match turning instructions with the surrounding. In one case, a married couple disagreed on the route, and the driver decided to not follow the instructions provided by her spouse but to decide on her own. However, overall, drivers trusted the passengers' advice more than an automatically generated command. As an implication, future systems should be able to individualize the amount, type and timing of information to take prior experiences and personal knowledge of drivers into account. As this remains challenging, integrating the passenger might be a way to support the driver.

Laurier et al. [161] analyzed several video-recorded trips of couples and groups with varying backgrounds. They found passengers to be in the role of a guest, and the situation similar to the one when sharing a flat or an office. Passenger often do not want to interfere with the drivers' habits, and will ask their host before adjusting controls. However, they also state that *passengering* is more than just being driven from A to B. Especially the front-seat passenger is usually aware of the traffic situation as well as the driver's actions, and often gets involved in the demands of driving by supporting deliberately or on request, and thus can be seen as some kind of "crew"-member [161]. Adding to that, Heikkinen et al. [103] observed that driver and passenger tended to distribute certain tasks consciously among them. For example, the passenger took responsibility for the interaction with the navigation device and gave turn-by-turn instructions, so that the driver only occasionally had to glance at the device himself. Similar, accessing news or social media updates can be mediated by the passenger, who is able to filter the information based on the driver's interest.

The presence of a passenger can impact driving safety. Regan and Mitsopoulos [223] investigated how driving behavior changes when a passenger is present. They highlight the potential of the "extra set of eyes" that drivers might benefit from, but also point out that, especially for young drivers and male passengers, this effect can be negative when drivers want to prove themselves and show off. Positive effects have been observed when the passenger helps the driver with the navigation task, or performs other tasks for the driver, such as answering the phone or adjusting temperature dials. Moreover, the passenger can keep the driver company which is especially useful for longer trips, and alert the driver when speeding. On the one side, this can be annoying, but on the other side, exceeding the speed limit is sometimes done unconsciously and unintendedly. Klauer et al. [153] confirmed the positive effect of passengers, at least in the group above the age of 18. They found a lower risk for a crash or a near-crash involvement when a passenger was present compared to when no passenger was accompanying the driver in the vehicle. This *protective effect* [193] can be explained with the fact that a passenger also watches the traffic situation and thus "can warn a driver of an impending dangerous situation" [153]. Those assistance situations can be classified to be conscious/unconscious, explicit/implicit, or verbal/nonverbal [186].

Integrating the passenger's mental and manual capacity in the interaction can potentially help to improve travel safety. Inbar and Tractinsky [122] claim that the basis for a successful cooperation is that all parties share the same knowledge for example on the vehicle's current status. One important question they raise is "How [can] drivers transfer some of their tasks to passengers, while remaining in control?" [122].

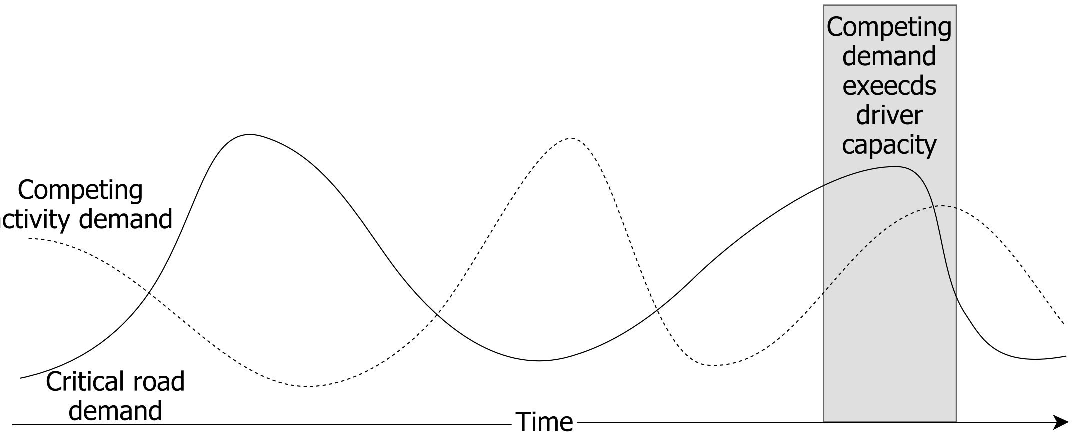

Figure 2.2: Curves representing the critical road demand for attention emerging from the driving task and a competing activity demand emerging from a secondary task. Distraction occurs when the overall demand exceeds the available attention (from [164]).

2.1.2 Basic requirements

When designing an infotainment system, one needs to fulfill not only the traditional user interface requirements like learnability, efficiency, error handling, memorability and satisfaction defined by Shneiderman [266], but also car-specific requirements like interruptibility, prevention of distraction, and readability [62].

Definition of driver distraction

In order to drive safely, the driver's attention is normally directed towards the road in front of him. This is important to observe the traffic situation and, as a result, to be aware of potential hazards. Consequently, one can detect critical situations immediately and react appropriately. When performing additional non-primary tasks, the attention is split between the roadway and the competing activity. Both attention demands vary depending on different conditions [164]. For example, the roadway demand is comparatively low when driving with 30 km/h in a quiet area, whereas it is high when driving in a complex multilane crossing situation with a lot of other road users. A driver can consciously decide to perform a non-primary task when he has ensured the roadway demand is low; but certain distracting incidents can occur all of a sudden, and raise the demand of a competing activity immediately.

Taking such varying conditions into account, Lee et al. define driver distraction as a "diversion of attention away from activities critical for safe driving toward a competing activity" [164]. This means that not every secondary interaction causes a crash. Figure 2.2 depicts the demands of two simultaneous tasks. Each of them can be rather high, as long as the other one is moderate. Critical situations arise when the overall demand for attentions exceeds the available amount and attention must be shared. The driver is then distracted from the primary task and fails to direct sufficient attention to the road.

There are different categories of distraction [193]:

- Visual distraction: Tasks that require the driver to look away from the roadway to visually obtain information.
- Manual distraction: Tasks that require the driver to take a hand off the steering wheel and manipulate a device.
- Cognitive distraction: Tasks that require the driver to avert the mental attention away from the driving task.

In the real world, there are serious consequences when distraction becomes too high. In research, especially in early phases, user studies are thus mainly performed in artificial settings such as driving simulators. When evaluating secondary interaction in such an environment, it is important to highlight the negative consequences of poor driving behavior [92]. For example, Harvey et al. [97] conducted a user study simulating a complex driving situation with several lanes, a high amount of traffic and crash simulations when driving performance was poor. Comparing different input modalities with a baseline drive, it became clear that in a complex driving situation, secondary tasks have a negative impact on the primary task performance, even in the simulator environment.

In domains such as mobile device interaction and wearable computing, the term "eyes-free" has been used a lot to describe interaction that does not require visual attention but allows to focus on a different main task [31]. Solutions are often based on voice or gesture recognition. Those have been shown to reduce visual distraction [10]; however, speech-based interaction as an alternative to traditional visual-manual tasks can also have a negative effect on driving performance compared to distraction-free driving. Lee et al [163] showed that both simple and complex email tasks affect how quickly participants react to critical traffic events; subjective workload ratings confirmed these results and indicated that the secondary task, especially more complex ones, introduced a significant workload and as a result, cognitive distraction.

Klauer et al. [153] investigated the reasons for crash and near-crash situations in a naturalistic driving study. They found that engaging in moderate (requiring at most two glances and/or buttons presses), and highly complex (requiring multiple steps) secondary tasks led to a doubled or even tripled crash or near-crash risk than when driving without a secondary task. However, they also state that secondary tasks only account for about one quarter of incidents, about the same amount as "drowsiness". Therefore, the authors come to the conclusion that secondary task engagement raises the risk, but there was no evidence that single short glances but only glances longer than 2 seconds lead to a critical diversion of attention, compared to baseline driving.

Regulations, standards and measures

There are many factors inside and outside the car that can influence the demand for attention for the roadway, and in turn the remaining amount for further activities. Still, there are some clearly defined guidelines and requirements for the development of in-vehicle information system (IVIS).

They cover a lot of potential situations that might occur on the road, and aim to ensure an equal safety level across different manufacturers.

The International Organization for Standardization (ISO) has published several standards to define ergonomic aspects of transport information and control systems. ISO 15005 [124] specifies principles for dialogue management that aim at interruptibility of secondary tasks to focus on the driving task. A driver should always keep one hand on the steering wheel. Moreover, single information portions should be small and easy to perceive to keep single glances below 1.5 seconds, and avoid continuously required visual attention. Feedback should be given within 250 ms, the modality is not specified. One should aim for a consistent interface design, where related functions have a similar presentation, for example regarding location, orientation, size and coding, to make functionality easy to understand.

Specifications for the technical requirements for visual presentations are covered in ISO 15008 [125]. For example, it specifies measurement methods for brightness and contrast, as well as minimum dimensions of characters (e.g. a size of 20 arcminutes is acceptable if color is a coding dimension). Furthermore, it defines the behavior of dynamically displayed content. This covers for example blinking behavior, which should be avoided except for situations in which immediate attention is required, but also dimming amount and speed for different light situations.

ISO 3958 [123] presents hand-reach envelopes (in German: "Greifschalen"), which specify the boundaries of locations in which the driver can perform a *basic reach task*, which in turn is defined as controlling a 25 mm control knob with a three-finger grasp without lifting the interacting arm's shoulder off the seat. The environment is characterized as "the non-reaching hand on the steering wheel and the right foot on the accelerator pedal" [123]. Further hand-reach envelopes, *extended-finger-operated* and *full-hand-grasped forward control*, extend or reduce the basic envelope by 50 mm. Moreover, restrained and unrestrained reach envelopes allow for either 100 mm or free shoulder movement. For this thesis, interaction is restricted to the restrained reach envelope.

The European Union publishes recommendations on safe and efficient IVIS as a part of the "European statement of principles on the design of human-machine interface" (ESOP) [47]. It aims at different parties that are involved in the design of in-car systems, namely

- Vehicle manufacturers offering in-vehicle devices with information and communication functionality
- After-market system and service producers
- Providers of nomadic devices, intended to be used by a driver while driving
- Manufacturers of parts enabling the use of nomadic devices by the driver while driving (e.g. cradles, interfaces and connectors)
- Service providers including software providers or broadcasters of information meant to be used by the driver while driving, e.g. traffic, travel and navigation information, radio programmes with traffic information

This emphasizes that driving safety is not only the responsibility of car manufacturers, but of everyone who designs interaction or builds devices that are used in the car. In the statement, several design goals are presented. Those are in line with the definition of distraction cited before [164]; the system should be easy to understand and not distract, but enable the driver to choose whether, when and how an interaction takes place. The driver needs to be able to direct the attention to the driving task that is required to cope with the current demand. Moreover, the recommendations contain design and installation principles for different categories. Those range from "The driver should always be able to keep at least one hand on the steering wheel while interacting with the system" [47] to "Visual displays should be positioned as close as practicable to the driver's normal line of sight" [47]. The latter is specified in more detail; displays that contain relevant information and where long glance sequences are expected, should not be placed below approximately 30° downward the viewing angle of the driver's normal forward view. In most current car models, this covers the area of a central information display (CID) and further down about the upper two thirds of the center stack.

Building upon the ESOP guidelines, the "Driver Focus-Telematics Working Group of the Alliance of Automobile Manufacturers (AAM)", a union of car manufacturers, has published the "Statement of Principles, Criteria and Verification Procedures on Driver Interactions with Advanced In-Vehicle Information and Communication Systems" [4]. It provides more detailed information and criteria that have to be achieved when designing in-car systems. The guidelines are limited to the design of new infotainment systems that are intended to be controlled by the driver under routine driving conditions, specified as "not exceptionally demanding" [4], e.g. following another vehicle in an unfamiliar area. For example, to meet the criteria of glance duration, 85% of the test sample should not exceed 2 seconds for an average single glance (Criterion A1), and not exceed 20 seconds for a whole task (Criterion A2).

The National Highway Traffic Safety Administration (NHTSA) in the USA gives out guidelines [193] for in-vehicle electronic devices that are controlled through visual-manual means. They claim that from police-reported crashes, 3% of all distraction-related incidents are caused by the interaction with infotainment systems, so they aim to "promote safety by discouraging the introduction of excessively distracting devices in vehicles" [193]. Examples of recommendations are not to include video and automatically scrolling text, and not to allow manual text entry to perform text-based communication or internet browsing. Moreover, displaying any text and graphical or photographic images should be avoided. Overall, interaction with the infotainment system should not require glances longer than 2 seconds and cumulated glance durations for a single task of more than 12 seconds. Implementing these guidelines would mean to exclude most of the functionality available in current in-car systems, at least for the control during driving.

Evaluation of automotive user interfaces

There are different methods to evaluate IVIS and to assess their potential to distract the driver. Apart from preliminary and qualitative investigations, such as expert evaluations, model-based predictions can serve to provide estimates of user behavior. Furthermore, systems can be evaluated in real world scenarios or in driving simulator environments.

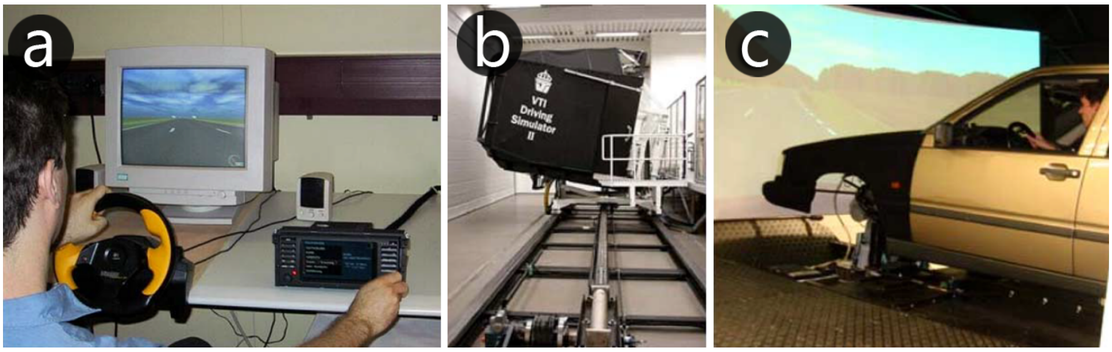

Figure 2.3: Driving simulations can be set-up in different levels of fidelity. a: Lane Change Task setup (picture from [180]) b/c: dynamic driving simulation (picture taken from [67]).

Qualitative pre-evaluation In an early phase of development, qualitative evaluations such as expert discussions can give an indication if a concept idea is valid and worth to follow up.

Pro: An advantage of a qualitative pre-evaluation is that it does not require much preparation but only a means to communicate the idea. This does not have to be a fully functional prototype, but can for example be a paper prototype that can serve to explain the principle, or to demonstrate how some program logic is intended to work.
Con: The simplicity of early evaluations can also be a drawback. Without a fluidly working prototype, the user might not be able to understand how it *feels* to use a system. In rough sketches, details might not be defined that can influence the experience. To improve the understanding of the automotive environment, discussions can be conducted in the car or while driving, as people might be more aware of potential influencing factors.

Model-based evaluation Behavior models can be used to predict user performance. Salvucci [250] combined existing models of driving behavior with models of different interfaces for secondary tasks. Thereby, an a priori prediction of the dual-task performance can be calculated. A study with human drivers in a driving simulation showed that although models cannot predict the exact variation in human behavior, it can provide the researcher with overall patterns of effect.

Pro: Behavioral models can predict patterns of effects that appear when using different interfaces to perform a task in addition to a primary task.
Con: Behavioral models are required, thus need to be either available or to be developed. This may not always be applicable, especially when the prediction should be carried out on more complex tasks.

Driving simulator evaluation One step further in terms of fidelity, driving simulators can be used to conduct user studies where the interplay of primary and secondary tasks can be experienced. The levels of realism range from simple setups, like in the standard *Lane Change Task* (LCT) [180], which allows for a reproducible study design and offers a standardized analysis, to high-fidelity setups such as in dynamic driving simulators (see Figure 2.3). They simulate centrifugal and acceleration forces that occur when driving, by moving the platform on which the mock-up is standing. Driving scenes are presented on screens or on up to 360 degree projections around the mock-up. Bach et al. [10] compare the results of a study performed in both a simulated static driving facility and in a controlled driving environment on the road: they found similar patterns regarding task completion time, interaction errors and glance times for the secondary task. However, they report that the results regarding longitudinal control for the simulated driving were worse, and they trace back to the missing movements in the simulator environment. Overall, simulated driving can give good indications for the results in a real driving environment.

Pro: Simulations provide an environment where independent variables like critical driving situations can be triggered in a controlled manner. Secondary tasks can be evaluated while performing a driving task, but without the risk of an accident. Prototypes that are not yet ready to be built into a car, for example because they are too bulky, or not resistant to sun light or vibrations, can be evaluated in a dual-task driving scenario.
Con: Driving simulations are still artificially built environments. Depending on the fidelity-level, it can be hard to put oneself in the context of a real car ride.

The Alliance of Automobile Manufacturers (AAM) [4] states that it may not always be possible to carry out road studies or extensive simulator studies, especially for early design phases. For quick evaluations, a simple static divided-attention test can be used to measure visual distraction of a secondary task. As a primary task, the participant has to focus on a road scene. For example, a video of a driving-like scene can be used that contains prominent visual events. Then, the user has to react to or remember those event, and primary task performance can be measured by reaction speed or recall rate. Underwood et al. [287] have performed evaluations of glance behavior through watching pre-recorded videos. Afterwards, they asked participants to recall situations they had just seen. They found similar patterns regarding glance durations and recall rates as found in real driving situations, indicating that concentrating on a driving video can at least to some extent mimic live traffic observation.

Real-world evaluation For evaluations that are conducted in real traffic, prototypes are often in a final stage of development.

Pro: Real-world evaluations consider a wide range of influencing factors. This is useful to see how an interaction integrates into everyday life and what factors influence the performance.
Con: Driving on real streets with real traffic requires participants to cope with situations that are much more critical than in a simulator where an accident does not have severe consequences. Therefore, it is not possible to perform studies in early stages of the development process, when the impact of secondary performance can not be estimated. A further drawback is that the study environment can not be controlled. There are a lot of distracting factors in real life, such as traffic, light conditions, sudden detours, or attention-grabbing advertisements. Those influence visual and cognitive load, and effects of secondary tasks are more difficult to detect and verify.

For the evaluations while driving, may it be in real traffic or a simulator environment, qualitative as well as quantitative measures regarding primary and secondary tasks can be taken.

On the one hand, attention and workload have been found to influence distraction, and in turn *primary task performance*. This can be measured as longitudinal and lateral deviation from a given value, speed reduction or reaction times to critical events. The AAM [4] defines standardized test settings for either road or simulator studies (whereas they state it might be difficult to create reproducible conditions in a real world setting), including roadway settings, speed, traffic situation, as well as a reference task procedure. Criteria for lateral-position control, or lane keeping quality, can be measured as numbers of lane-exceedances. Following headway ability, i.e. how good a the driver can keep a specified distance to another vehicle, is reflected in the reaction to speed changes of a front car or in the calculated time to collision (TTC) [293]. Further objective measures are physiological parameters, such as skin conductance response and body temperature, which have been shown to mirror subjective workload ratings [256]. Visual distraction can be evaluated by observing glance behavior. Number and duration of glances towards specific areas (road scene, displays) can be measured, with either head-mounted devices such as the Dikablis tracking system by Ergoneers[2], or a stationary mounted system such as the one by Tobii[3].

On the other hand, a common dimension of measurement for *secondary task performance* is workload, which can be obtained with questionnaires such as the *NASA Task Load Index (TLX)* [96] or the *Driving Activity Load Index (DALI)* [205]. User experience and the fulfillment of psychological needs are measured with the *AttrakDiff* questionnaire [99]. It discriminates pragmatic quality (PQ), which explains whether or not the system fulfills functional goals by providing useful and usable means, and hedonic quality (HQ), which describes whether it helps to fulfill individual needs, such as the desire to improve oneself or to communicate with others. A standard measure for usability is the *System Usability Scale (SUS)* [32]. Moreover, task completion time and errors give objective numbers on task performance.

2.1.3 Research directions

Since decades, researchers are trying to reduce the distraction which is caused by interacting with a growing amount of functionality. The conference Automotive UI[4], which was founded 2009, has a strong focus on user interface research in the automotive domain. Approaches reach from the evolutionary development of existing systems to new display concepts, new modalities for user input and to new kinds of feedback delivery. Direct touch is one promising direction that combines in- and output.

Further developing remotely controlled systems

Currently, the predominant interaction device for infotainment functionality is a central, multi-functional rotary controller, which is placed within easy reach at an ergonomic position in the center console and which comes in conjunction with a central information display. Examples are BMW iDrive, Daimler COMAND or Audi MMI. The controller has a restricted number of

[2] `http://www.ergoneers.com/de/products/dlab-dikablis/overview.html` [cited 2013/11/15]

[3] `http://www.tobii.com/` [cited 2013/11/15]

[4] `http://www.auto-ui.org` [cited 2013/11/15]

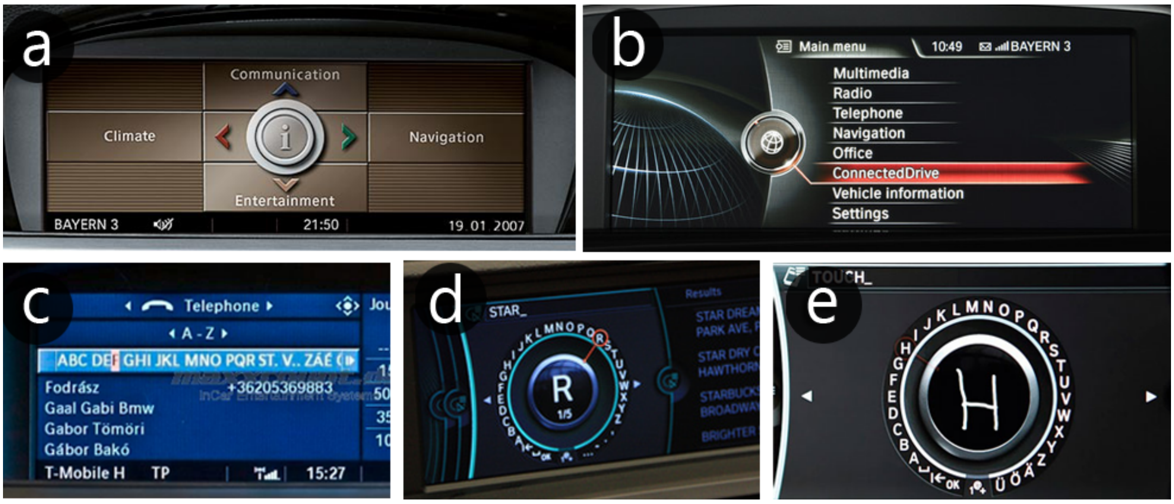

Figure 2.4: Evolution of the BMW iDrive system[6]. a/b: Menu structure from 2001 and 2013. c/d/e: Text input via a rotary controller from 2001, 2008 and 2012.

degrees of freedom, namely

- turning (*clockwise*, *counter-clockwise*),
- shifting (*east*, *south*, *west*, *north*, possibly additional intermediate stages),
- pressing.

Menu interaction needs to be mapped to those. Car manufacturers continuously improve those mappings to ease the interaction with remote controllers. Figure 2.4 shows the evolution of the BMW iDrive menu. The first version used four shift directions to access submenus and a cube metaphor, while in the version of 2013, a vertical list and overlapping submenu layers are used to improve the overview of available functionality. Another example is the mechanism for text input. The early horizontal character list was replaced by a radial character representation. To reduce the number of required steps for text input, different manufacturers have recently added the new degree of freedom

- touch sensitivity

which allows for recognition of handwritten input on top of the controller.

Remote touch sensitivity can also be integrated without adding it to the remote controller, by integrating an (additional) touchpad in the center console. Daimler presented *Cam-Touch-Pad* [183], a touchpad with distance-sensing, that displays the hand's outlines schematically on the central screen. Thereby, the user can see the interacting hand hovering over the displayed interface without covering the screen's content. Touching the surface corresponds to confirming the current

[6] © Photos BMW Group.

selection. A similar interaction was realized by Lexus' *Remote Touch* system[7], a joystick-like device featuring additional buttons to confirm a selection on the screen. Haptic force as well as pointer size are adjustable.

PRO	**CON**
Haptic feedback	Indirect control
Ergonomic position of remote controller	Mapping of restricted degrees of freedom to content

Table 2.1: Benefits and drawbacks of remotely controlled systems.

Remotely controlled systems with a multifunctional controller and a CID often focus on transferring the WIMP (Window, Icon, Menu, Pointer) metaphor from personal computers to the car instead of developing novel interaction concepts for automotive user interfaces.

Keeping the forward viewing direction

A key problem of the traditional visual-manual controls is that the road scene vanishes from the line of sight when the driver glances on the head-down displays (HDDs) such as CID or instrument cluster (IC) (see Figure 2.5). Keeping the forward viewing direction means to display visual content not in the area of a center stack or instrument cluster, but in the normal line of sight. Using an automotive head-up display (HUD) or head-mounted display (HMD), the content is presented as an overlay to the road.

Ablaßmeier et al. [1] compared glance behavior when using either head-up or head-down display. They found that the gaze retention period, which is defined as the time it takes to capture information, including both fixation and movement periods, is shorter with head-up displays. The effect grows with increasing complexity of the traffic context; when driving on interstates, the diversion time was about 15% shorter with HUDs, whereas, when driving on heavily traveled city roads, an average reduction of up to 25% took place. When diverting visual attention from the road to some displayed content, the eye must be adjusted to the new focus plane. When accommodating from an object at a 5 m distance to either a HUD display (2 m), and an instrument cluster (0.8 m in front of the user), Inuzuka et al. [126] found that the amount of accommodation is lower for the HUD, which contributes to shorten the gaze retention period.

Milicic [187] compared the interaction with different positions for the presentation of content. Letting participants interact with a menu structure in either HUD or CID, in different real driving situations such as city ride, highway and freeway, the overall glance strategies differed for the different display positions. There were more glances towards the CID; glances towards the HUD, however, were longer. For both locations, AAM criteria for glance durations were met. Overall, secondary as well as primary task performance were better with the HUD, which might be due

[7] Brian Gill: Point & Click: Lexus' Remote Touch system ushers in a new age of vehicle systems control. `https://secure.drivers.lexus.com/lexusdrivers/magazine/articles/Vehicle-Insider/Remote-Touch-System` [cited 2013-11-02]

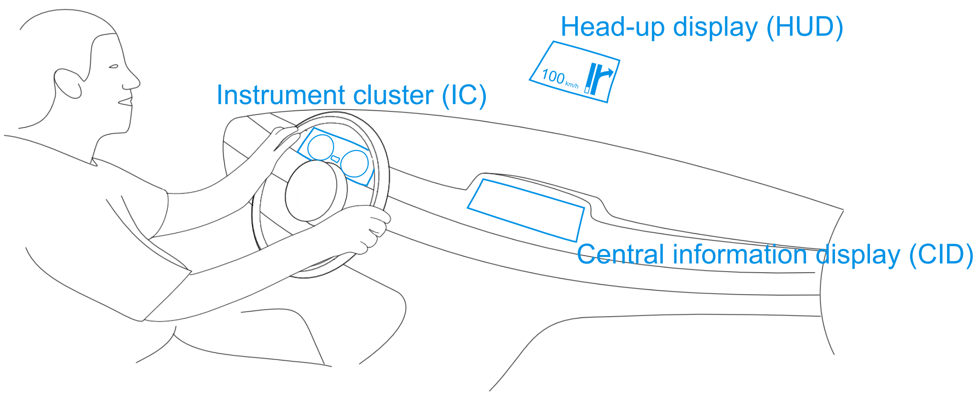

Figure 2.5: Display areas in the car.

to the parafoveal perception of the road scene when interacting with the HUD. For example, there were less driving errors (according to Schweigert [259]); especially lateral control was less influenced by the secondary task. Overall, HUDs are recommended for simple and frequent tasks.

Building upon these results, Ecker [61] further compared the use of a HUD with other display locations (CID, IC). He worked on the optimal design for a list-based user interface presented on the HUD. Independent of the display location, overall glance times could be reduced by increasing the number of list entries, because the number of hierarchical levels goes down. He suggests the use of seven list items to reduce glance time. AAM criteria were missed when using the HUD, but driving performance was slightly better than with IC and CID. In a further experiment, the different available displays were combined to multiple coordinated views, which allowed making use of the potential of the HUD while AAM criteria could be fulfilled.

Weinberg et al. [300] compared HUD and HDD, both controlled with a steering wheel-mounted jog dial device, to an auditory interface. The HUD was preferred compared to a HDD regarding ease of use and showed a significantly lower workload. Auditory feedback was significantly slower to use than the HUD. Moreover, the HUD showed a high user satisfaction. Overall, the authors suggest to apply a multimodal approach, and combine HUDs with auditory interfaces, for example by displaying choice lists in the HUD, and using speech to select items and confirm a choice.

Foyle et al. [76] found that HUDs can have a negative impact on the ability to perceive changes in the environment, even if those are in the direct line of sight; this phenomenon is called "cognitive tunneling" [291]. The effect was reduced when not directly superimposing different information. This indicates that for example eye movements can help to prevent attentional capture [76].

The development of current HUDs aims not only towards presenting content in a restricted display area, but to extend it to augment the environment. This can either be realized on a larger HUD or on a see-through HMD. Like in smartphone applications such as Wikitude[8], this could allow displaying location-based information at the position where it is located in the environment.

[8] http://www.wikitude.com [cited 2013/11/18]

In general, information in augmented reality (AR) environments can be classified according to the way it is displayed [150]:

- **World Fixed**: The displayed content is associated with a specific location in the world (e.g. a building). This category is sometimes called *contact-analog* in the automotive domain [214].
- **View Fixed**: The displayed content is always at the same position in the field of view (e.g. on the top border), and moves according to movements of the user.
- **Object Fixed**: The displayed content is associated with an object in the world (e.g. moves with a pedestrian).

AR visualizations can reduce the cognitive load that arises when information has to be mapped from the presentation on a CID to the real world. Kim and Dey [152] compared those to traditional display usage for navigation information. They found less navigation errors, and less critical driving situations, for drivers of all ages. AR visualizations have also been shown to reduce visual distraction from the road scene which led to better driving performance, compared to navigation systems displayed on a CID, no matter if those were based on arrows or augmented street view presentations [182].

This effect, such as most results of AR visualizations, has been shown in a driving simulator. Results in real-world situations might differ, when visualizations are influenced by changing weather and brightness conditions and motion and position sensor data; robust hardware is still hard to get.

PRO	CON
Line of sight remains on the road	Cognitive tunneling
Shorter eye movement and accommodation times (HUD) compared to HDD	Problems with size of HUDs and stabilization of HMDs
Direct mapping of location-based information	Only for the driver (HUDs) or wearer (HMDs)

Table 2.2: Benefits and drawbacks of HUDs and HMDs.

Making use of new input modalities

A further way to improve interaction is to make use of new modalities to interact with the infotainment system.

Speech input Speech recognition systems allow the user to interact with a system by issuing speech commands. In early systems, only the use of certain keywords was possible, to ease the recognition of commands. This required the user to be aware of the available command list, and sometimes even the current domain. The next step is now to integrate dialogue systems that allow for natural spoken queries [263].

Performing a destination entry task, speech input outperformed visual-manual input in terms of task completion times as it required less interaction steps [281]. Gärtner et al. [83] have integrated a speech-based driver information system into a car and have conducted a study comparing it to a visual-manual system. The speech-based system caused less visual distraction and therefore more glances towards the road scene and towards the mirrors; however, visual representations of the spoken input confirming the correct recognition caused visual distraction again. For both simple and complex tasks, which required 2-3 and 6-8 steps, respectively, speech input induced longer interaction times due to the extended processing and verification times. Speech-based systems can reduce visual distraction, however, they have been shown to increase mental load. Lee et al. [163] compared reaction times to critical traffic events when performing a simple as well as a complex email task. Both showed to demand cognitive capacity, which resulted in a decrease of performance compared to the baseline where no task was performed.

Speech is a modality that is often used in combination with other modalities in multimodal systems. Cohen [45] argues for a combination of speech and direct manipulation. Natural language can be used to issue detailed descriptions of entities, locations and tenses, whereas direct manipulation allows to directly engage with apparent objects. Weinberg et al. [300] propose to display available options for interaction in a HUD, for example when the recognition accuracy is poor.

PRO	CON
No manual input required	Requires mental capacity
Suitable as an additional modality	Commands need to be known in advance (command-based)
Can reduce the number of interaction steps	Uncomfortable issuing of speech commands in the presence of others
	Performance of speech recognition systems

Table 2.3: Benefits and drawbacks of speech input.

Freehand gestures Freehand gestures are performed in the free space next to the driver and should not be confused with gestures on a touchscreen. With the advent of gesture control in CE devices such as the Microsoft XBox in combination with the Kinect[9] in 2010, the interest in gesture control for automotive user interfaces has strongly increased.

Gestural interfaces have been shown to reduce visual demand and in turn increase safety [231]. In 2005, Althoff et al. [5] investigated the recognition and application of a gesture set consisting of 17 hand and six head gestures, which they used for menu and content interaction. Gestures were performed in the region above the gear switch. For example, directional swipes served to skip

[9] `http://www.xbox.com/kinect` [cited 2013-11-19]

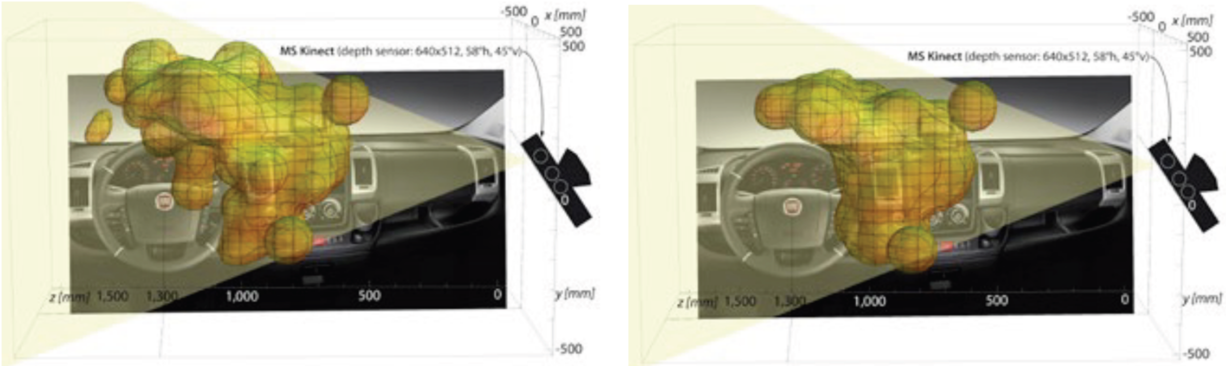

Figure 2.6: Density plots of the execution area of car-control (left) and media control (right) functions, taken from [232].

between individual music tracks, or to navigate in a map. They highlight that by incorporating contextual information, the gesture set could be reduced. As a result, the remaining gestures could be interpreted more robustly, learned more easily, and could lower entry barriers. Using remote proximity sensing, Riener and Wintersberger [233] applied two-dimensional movements to control a cursor on a CID. They did not yet integrate a movement to confirm a selection, but proposed to use an additional button or sensing in a third dimension.

Gestures can also be used in the free space around the steering wheel, while keeping the hands in contact with it, and therefore reduce manual distraction as recommended in the NHTSA guidelines. On the other side, it restricts possible movements. Mahr et al. [177] designed a reduced set of three micro-gestures, a two finger zoom gesture, an index finger sweeping gesture and a circular movement of the index finger. They found that the sweeping gesture was regarded as less preferred in comparison with the other gestures as they were more ergonomically demanding. Fujimura et al. [79] investigated pointing gestures for the interaction with content in the environment that is in turn highlighted using a 3D HUD to confirm a selection. They used a depth camera for gesture recognition, mounted on the dashboard to capture finger gestures from the front, and thereby achieved very robust tracking with a high accuracy and stability.

Riener et al. [232] investigated the space in which a user would like to execute gestures. Participants were presented with a task and asked to think of an appropriate gesture and execute it. Figure 2.6 shows the execution areas for car- and media-related tasks. Most of the gestures were executed in a triangular region between steering wheel, rear mirror and gear shift, and took on average 1.9 seconds. Individuals showed a low intra-gesture variability: they predominantly chose a specific gesture for one task and performed it similarly each time. What the study showed, however, was a high inter-gesture variability between individual participants. For many functions, even for functions with an inherent direction, gestures were executed differently (e.g. performed with the palm up or down, with a single finger), indicating that the mapping of gestures is a very complex task.

PRO	CON
No visual attention required	Ambiguity of recognition
Current CE topic	Number of possible gestures
	Visibility from outside
	Mapping of gesture to function

Table 2.4: Benefits and drawbacks of freehand gestures.

Gaze input Eyetracking systems can not only be used in the evaluation phase to analyze how visual attention is distributed, but it can also be used for the interaction with the system – either explicitly or implicitly. Gaze has been shown to be a viable alternative to keyboard and mouse for different selection tasks in gaming environments [130]. Problems can occur when a continuous eye movement is used to define a motion path due to apparent involuntary gaze jumps [130].

Kern et al. [143] have applied gaze as an explicit interaction modality in the car, in combination with a button on the steering wheel. A user has to *look* at a certain element on a screen, and *click* for selection, to directly interact with visual content. This process is similar to touch interaction, but without the need to take a hand off the steering wheel, and the need to place the screen in direct arm reach. A study comparing gaze, touch and speech to a baseline showed, as expected, a significant decrease in driving performance for all systems. Gaze was worse than touch in terms of driving performance, and interaction speed, and faster to use and less error-prone than the speech interface. To improve interruptibility of gaze-based interaction, Kern et al. introduced *Gazemarks* [142]. Those ease the orientation after resuming an interrupted task by highlighting the latest gaze focus region. Stellmach and Dachselt [274] suggest gaze-supported interaction to overcome inaccuracies of gaze selection. Gaze is used for preselection while manual input is used for fine positioning and confirmation.

Poitschke et al. [216] investigated gaze control for the interaction with a CID. An element is chosen by fixation on the respective element. Further interaction is then performed with gaze or a scroll-wheel. In a comparing study with a direct touch concept, gaze interaction caused higher cognitive load, measured as longer reaction times and less detected peripheral detection task (PDT) events. There was, however, a strong learning effect; expert gaze users performed better with gaze than with touch. Overall, selecting a widget with a short glance and further interacting with a different modality can make use of of the quick direct selection but avoids long fixations on the object to be changed.

As an example for non-explicit use, Ecker [61] used gaze-based interaction to implicitly choose the interaction space that is controlled with a hardware control device. As a result, there is no need for an explicit step to select the current interaction space, or to switch to a different input device. In a comparison with an explicit change of the input device, he found no differences in glance behavior and overall glance durations. As only one input device was used for different display spaces, DALI results showed a lower tactile effort; all other workload dimensions were not significantly different.

PRO	CON
Hands-free	Visual attention is required
Direct interaction with (display) objects	Interaction speed

Table 2.5: Benefits and drawbacks of gaze input.

Making use of non-visual feedback channels

Wickens describes a typical situation while driving as follows: "Driving along a crowded highway on a rainy evening, while trying to glance at the map and search the road side for the right turn off, the driver's cellular phone suddenly rings" [310]. There are many distracting events in the car; however, he claims that according to the multiple resource model, there will be less interference between primary and secondary task when those do not share the same resources in different stages of information processing. There are different approaches that replace visual responses with either auditory or tactile feedback, to avoid further visual load created from secondary task interaction.

Auditory feedback There are two types of auditory feedback in the car, that can be distinguished according to their purpose [133]: it can communicate information about the driving task, predominantly as warning sounds, or support the interaction with the infotainment system.

Politis et al. [217] compared different feedback modalities and their combinations for warnings of different urgency levels in a driving scenario. They found that additional audio feedback can improve the recognition time of visual warnings. Auditory feedback raised the level of annoyance, but at the same time, it communicated urgency very well. To improve the expressiveness of auditory warning feedback, Ho and Spence [112] used spatial sounds that add information on the source of warning. They compared it to non-spatial and verbal warnings ("back", "front"), and found that if an auditory cue contains directional information, reaction times to critical road events improved. They recommend the use of nonverbal signals as those "are less susceptible to the influence of other concurrent linguistic elements in the environment" [112].

For the interaction with an infotainment system, auditory feedback often comes in the form of text-to-speech (TTS) output. Jeon et al. [133] investigated the interaction with long lists, and compared a visual-only representation with one enhanced with TTS output that read out loud the currently selected menu item and its alphabetical position to not loose track of the ordering. They found a significant increase in primary and secondary task performance as well as regarding subjective preference for the auditory interfaces. Drawbacks of speech-output are that the output is serially processed and therefore interaction speed is low, which might cause it to be perceived as "lengthy", and that it can interfere with ongoing conversations [192]. For the output of whole sentences, it is important that language is easy, as complex sentence construction have a direct influence on cognitive workload [53].

Haptic feedback So far, many controls in the car are providing haptic feedback. When grasping for a switch, its size and texture provide information without the need to look at it. A control element with certain haptic properties is often assigned a specific functionality, for

PRO	CON
Hands-free	Interaction speed
No learning required	Interference with conversations

Table 2.6: Benefits and drawbacks of auditory feedback.

example a small rotary knob for volume control or a large rotary knob for climate control. With programmable rotary controllers, users can experience distinct haptic sensations for different applications [102], such as short strong ridges in long lists, and wider softer ridges when zooming into a map view.

Rydström et al. [249] tested an in-car interface showing a visual menu of four textures displayed on a screen and corresponding haptic information displayed through a remote rotary device. Turning the knob felt differently due to a varying amount and differently-sized ridges. When only provided with haptic information, participants' eyes remained on the road during the interaction. Nevertheless, the experimental task with only-haptic interaction took longer due to serial processing. The degradation in driving performance and mental workload assessment did not differ between only-visual, only-haptic and both combined conditions.

Haptouch [229] is a prototypical force-sensitive screen which can be moved in z-direction to provide a new dimension of input and output on touchscreens. Compared to a normal touchscreen, it showed reduced error rates and a decrease in task completion time. This was especially true for small interactive elements that are hard to perceive visually. It, however, has the same problem as most buttons that are built into current cars [146]: haptic feedback is provided when pushing a button. After that, it does not remain in a *pushed* state. No haptic, but only visual feedback in the form of icons or LEDs indicate the current state permanently.

PRO	CON
Direct feedback	Interaction speed for complex information

Table 2.7: Benefits and drawbacks of haptic feedback.

(Vibro-) tactile feedback Programmed tactile stimuli are perceived via the sense of touch. Tactile feedback can for example be provided in the form of vibrations. An alternative are electrovibrations [15]. The electrostatic friction between a touch surface and an interacting finger can be controlled by regulating the intensity of the electric current[10]. To be able to perceive the feedback, the finger must be moved on top of the surface.

Vibrotactile feedback in the car can serve as a means to output warnings, to "alert the driver about potential hazards or to raise his or her attention to further visual information shown on the display" [145], and has been shown to result in shorter reaction times than visual warnings [260].

[10] `http://senseg.com/technology/senseg-technology` [cited 2013/11/20]

Similar to auditory feedback, tactile information can support the interaction with the IVIS. For example, vibrations have been used to provide navigational cues. For this purpose, several actuators were integrated to be perceived on different body locations. For example, they can be integrated into the car seat, below the left and right thigh [288], into the steering wheel [144], or in a belt as an additional wearable device [7]. In *NaviRadar*, we[11] showed that continuous tactile cues presented by one actuator could provide pedestrians with an increased awareness of a navigation direction, without being obtrusive [242]. This indicates that vibrotactile feedback can not only alert, but also provide subtle information.

After vibrotactile feedback has been successfully used on the smartphone, it is now also used in the car to enhance touchscreens. To cope with the lack of feedback, vibrations can confirm a button click [212] or give feedbach when scrolling a list [198]. Besides a subjective preference for added haptic feedback, Pitts et al. [211] showed significantly reduced glance times. Referring to users' feedback, they highlight the influence of haptic touchscreen feedback on attitude towards and confidence with the interaction.

To allow for feedback before an interaction with a touchscreen has taken place, Richter [228] proposes to make use of remote tactile feedback (RTF). It spatially decouples the location of touch input and the location on the body where the tactile sensation is perceived. For example, when a finger is approaching an interactive element on the screen, feedback can already be given through actuators built into the seat.

PRO	**CON**
Direct feedback	Interaction speed for complex information
Unobtrusive	Only possible when in contact with the device (except RTF)

Table 2.8: Benefits and drawbacks of tactile feedback.

Easing interaction by direct touch

Touchscreens are increasingly integrated into the car. Most personal navigation devices (PNDs) come with touch functionality, so do current smartphones. They provide certain advantages in terms of usability but also pose challenges regarding the usage while driving.

Potential In comparison with state-of-the-art rotary controllers, touch provides advantages due to the direct interaction it allows. Harvey et al. [97] compared the interaction with 20 different secondary tasks, including music player and climate control. They showed that touch resulted in significantly higher *usability* ratings compared to a rotary controller, which was consistently rated low. One of the main disadvantages of the rotary controller is that lists can be only accessed

[11] The results have been published in: S. Rümelin, R. Hardy, and E. Rukzio. NaviRadar: A Tactile Information Display for Pedestrian Navigation. In *Proceedings of the ACM symposium on User interface software and technology (UIST '11)*, pages 293-302, New York, NY, USA, 2011. ACM Press [242]. The prototype was implemented by Sonja Rümelin in the course of her diploma thesis.

via scrolling which is time-consuming and requires attention. Connected to that, touch led to significantly increased interaction *speed*. This has not only been found compared to rotary controllers [97], but it has also been shown to outperform haptic devices like radio controls [10] as well as speech and gaze interaction [143].

Challenge However, those advantages come at the price of increased *glance duration*. Direct interaction is not supported with haptic feedback on current interactive surfaces, except confirming vibrotactile cues (see Section 2.1.3). Moreover, touchscreens are mostly mounted to the upper area of the cockpit to be well visible, which can lead to *fatigue* and the gorilla-arm-effect [313] when no support for hand and arm is provided.

Approaches There have been different attempts to cope with the challenges of touchscreens. One way to deal with visual distraction is to integrate appropriate feedback to lower the visual load (see previous section).

It is important to use touch for the things it is well suited for, as different modalities have different benefits. For example, for pointing and ballistic tasks, touch is preferred as it provides more degrees of freedom than for example a rotary controller, while for repetitive tasks and precision tasks, a haptic device is superior [236]. It might also be possible to redesign an interface to fit the new modality: changing continuous values like volume with + and - buttons that have to be hit precisely can be replaced by a slider [181] to make use of the potential of touch.

To avoid visual distraction caused by exact targeting of interactive elements, touch gestures on the screen's surface can provide a solution. Ecker et al. [62] have proposed *pieTouch*, a concept for menu interaction on a touchscreen. The pie menu appears where the user touches the screen, and items are selected by swiping towards them, making it possible to perform complex menu navigation blindly when the directions are known from former use. Quick unidirectional touch gestures, referred to as swipes, can also provide an easy means to switch between high-level domain overviews [301] or to call predetermined favorite functions. However, the set of swipes is limited and it is often difficult to determine which swipe gesture is best suited for a given function. Burnett et al. [37] conducted an experiment in which the participants could choose their own swipe gesture for a given task. Even in cases for which one direction seemed to be intuitive, such as a movement to the *right* for playing the *next* song, the participants selected different gestures due to different prior experiences.

To cope with fatigue effects, the hand or arm needs to be supported so that it does not have to fight gravity while interacting. This can for example be done by moving the touch input sensor to the hand and not vice versa (the hand to the touchscreen). Touchpads positioned in the region of today's rotary controllers allow that the arm can be placed on the armrest [34]. This can support the input of touch gestures and alphanumeric input. Haptic feedback can be given by snapping the whole device in its housing or with vibrotactile feedback [34]. Furthermore, Döring et al. [58] have developed a multitouch steering wheel that is controlled with touch gestures. Comparing an entertainment and a navigation task performed on the steering wheel to standard radio and navigation devices, they showed reduced visual attention towards the input device. Osswald et al. [201] also moved a touchscreen to the steering wheel, and found that low demand tasks, such as selecting an item from a list, cause a level of distraction comparable to simple physical tasks like unwrapping candy. However, they highlight the disadvantage of moving the visual output away from the the driver's line of sight.

PRO	CON
Usability (if designed accordingly)	Visual distraction
Interaction speed	Fatigue effects
Blindly issued touch gesture commands	

Table 2.9: Benefits and drawbacks of direct touch.

2.1.4 Conclusion

Different types of distraction, especially visual distraction, have been shown to increase the risk of unsafe driving behavior, resulting in an increased crash-risk. There are different recommendations and regulations that aim at reducing secondary task interaction that is not required for driving, and in the most extreme form to exclude them from the car. On the other hand, secondary tasks are heavily performed while driving, either with the in-car system or on nomadic devices, as people do not want to be limited and cut off from the outside world when sitting in the car.

It has been shown that it is possible to perform secondary tasks while still being able to distribute attention appropriately between road scene and side task. Secondary task can even have a positive effect. The interaction with the IVIS can break the monotony of driving [164]; cognitive load, induced by an auditory interface, has been shown to lead to improved lateral control [67], while talking to a passenger can help to stay awake in longer trips and lead to support with different kinds of tasks [223].

Therefore, this thesis will focus on ways to further improve or redesign the interaction in the car, to allow for not-car-related tasks, while making the interface compliant with requirements, such as ease of use, interruptibility and predictability, and allowing for safe primary task behavior. When developing ways to interact in an "eyes-busy environment" [301] such as the infotainment system in the car, it is important to observe the effects on glance and driving behavior.

The review of observational studies revealed that different people use a different subset of the available functionality, and that individualization of the interface is a promising way to ease the interface. Screen-based systems provide the possibility to adjust the interface as there are no fixed assignments of functions to hardware. Multifunctional remote controls offer a compromise to permanently assigned hardware keys. They consist of a haptic device that indirectly controls a screen-based system, while touch-based systems allow for direct control of the screen combining input and output. This offers advantages regarding usability and interaction speed, but also challenges, such as visual distraction and fatigue. However, there have been first successful attempts to circumvent these challenges. This thesis aims to further investigate ways to cope with the lack of haptic feedback that results in visual distraction. The focus will be on the haptic sense and on improving the manual component in visual-manual interfaces. The haptic sense is complex and includes tactile as well as kinesthetic perception. It is mostly unused when interacting on currently integrated touchscreen, but offers potential to improve interaction and feedback. The next section will introduce interactive surfaces and ways to redesign flat touchscreen surfaces. The way how control elements are designed today, supporting affordances and usability [90], can inspire the design of new surface shapes for touchscreens and will be investigated to enhance direct touch interfaces.

Essence

Secondary interaction plays a well-established role while driving. However, automotive user interfaces are subject to restrictions; for instance, visual attention must not be diverted off the road scene for more than a limited time interval, and manual interaction is restricted to particular hand reach envelopes. Visual-manual interfaces, namely touchscreens, allow to realize adaptive interfaces and support the direct manipulation paradigm. There have been approaches to compensate for the lack of feedback and to cope with the main challenges, visual distraction and fatigue. To follow up this path, properties of physical control elements can be taken into account.

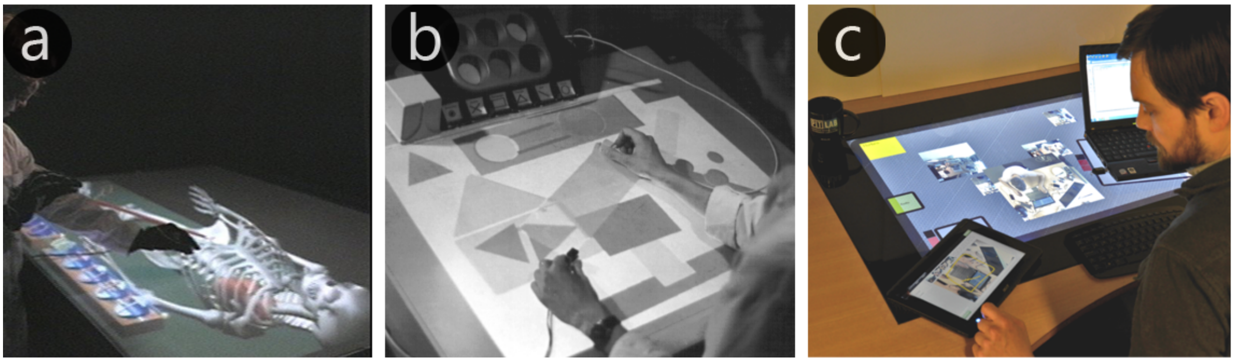

Figure 2.7: Approaches to control interactive tabletops. a: Interacting with data gloves with the *responsive workbench* [50], b: *ActiveDesk*, controlled with *bricks* [72]. c: *ActivityDesk* which allows to integrate further devices [120].

2.2 Interactive surfaces

In 1991, Mark Weiser's vision of ubiquitous computing [302] claimed that one day, our environment will be enhanced with invisible technology, providing appropriate access to information everywhere. This may be realized with location-aware tabs and pads for an office environment, replacing notebook and sheets of paper, and interactive boards that can be used either for writing or giving presentations, but also for accessing and manipulation of information on the go. In the following years, interactive displays were increasingly integrated into walls and tables, such as the *DigitalDesk* [309] that put the desktop metaphor of early graphical user interfaces back to the real desk. Digital desks made it possible to read and manipulate both digital and physical documents next to each other by the means of direct manipulation. Other examples (e.g. [157, 51]) used input modalities still based on tools known from virtual reality (VR), such as data gloves or remote controls (see Figure 2.7), not yet making use of the embodiment of virtuality for direct interaction. In 1995, Fitzmaurice et al. [72] introduced a new way to interact with interactive surfaces, to realize the seamless interaction between physical and digital world [129]: *bricks* are physical artifacts to extend interactive tables. They provide handles to interact on the flat surface of the table. Ishii and Ullmer [129] followed up by introducing tangible user interfaces (TUIs), which are designed to be physical objects with the possibility to represent and manipulate digital data. Until today, they have developed to be increasingly used as stand-alone tools integrating graphical output (e.g. [39, 101]), so they have become interactive surfaces themselves.

Apart from research projects, most commercially available interactive surfaces today are capacitive touchscreens integrated into smartphones, tablets, or, to a growing amount, automotive cockpits. To cope with the challenges posed by the trade-off between safety criteria and interaction requirements in cars described in the last section, this thesis will explore the design space that interactive surfaces open up for interaction.

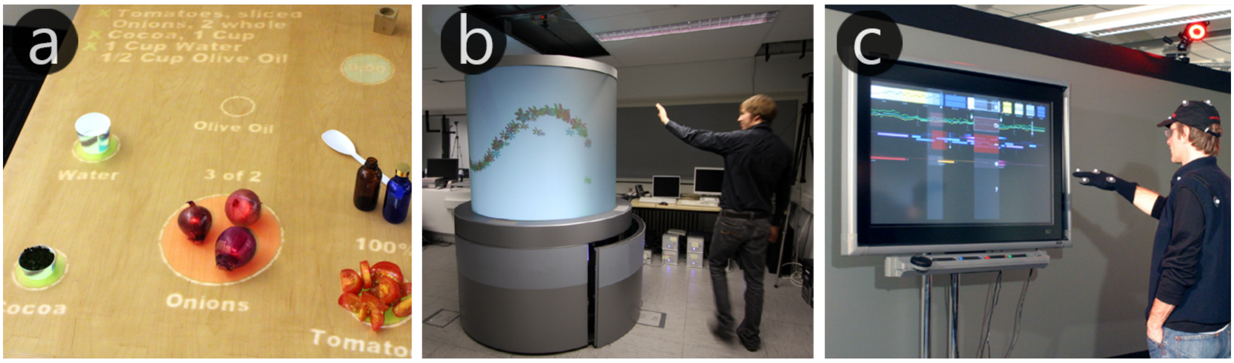

Figure 2.8: Interactive surfaces are often based on projection, with projection screens in different orientations and shapes. Examples are horizontal tables (with cooking instructions [316]), curved columns [23] and arbitrary landscape shapes [166].

2.2.1 Definition

The term *interactive surfaces* has been defined as "a heterogeneous class of human-computer interfaces which react to direct contact (...) and superimpose visual output" [228].

We are surrounded by the *surfaces* of things in our environment. Those can be made out of different materials, in different colors and shapes, and visually and haptically represent the objects behind them. Thereby, we can see and feel them. Augmenting surfaces with technology allows to make them interactive, adapt to dynamic contexts or present information. There are systems that were made to present low-density information with air bubbles [104], or using fog [220]. For higher-density information, interactive surfaces are often display surfaces, which can be oriented and shaped differently, resulting in horizontal, vertical or curved displays (see Figure 2.8).

Interactivity is the ability to react to input. Technically, this can for example be realized by touch recognition like applied in tabletops [313], or by gesture recognition so that content or presentation changes when the user is approaching or performs certain gestures [292]. Other possible input sources include sensor based systems, where an interactive surface might represent latest weather or activity data [292]. Interactive surfaces are often designed for collaborative work, so that several people can work together either in-place or remotely [66], sometimes incorporating physical objects to represent and manipulate digital data [110]. A reaction can be expressed in different ways. Visual output on a tabletop can change according to the actions that are performed with a digital object (e.g. [308]), but reactions can also be expressed as functional feedback [254] or even by changing a device's whole appearance [44].

Next step: Shape changing interactive surfaces

So far, interactive surfaces are solid objects which do not change their appearance more than by varying the graphical output. Due to technical improvements with materials such as dielectric electro active polymers and shape memory alloys (SMAs) [237], they could become organic in the next step, i.e. change their shape according to the current state of data [105]. Ishii, who had earlier inspired the research on TUIs, envisions the next step for human-machine interaction in

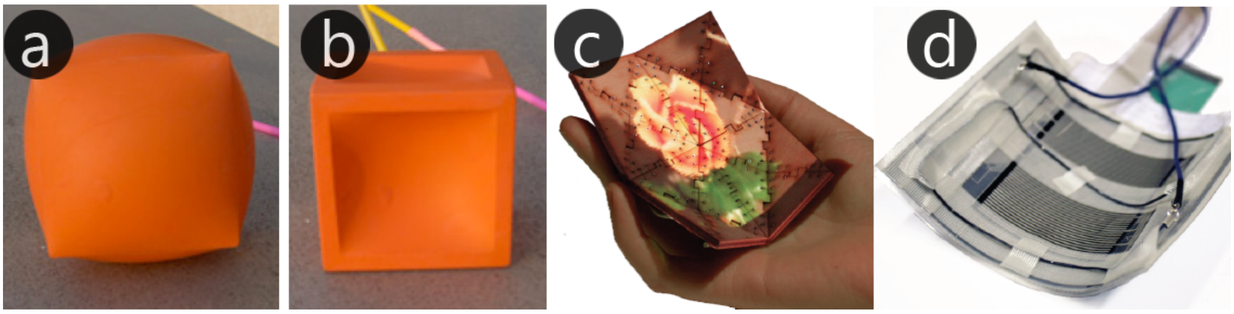

Figure 2.9: Examples of interactive objects changing their surface shape. a/b: Morphing harddisk [117]. Prototypes show the potential of new materials. c: Thin SMA wires applied to thin wood tiles. d: Flexible touchscreens [237].

completely new dynamic materials, *radical atoms* [128], that can be reconfigured if necessary to match the digital data it represents.

Deformation can have different functional aims [222]. A change of shape can communicate information, such as the *Morphing Harddisk* concept [117] that indicates its remaining space through the surface which is either sucked in or blown up. Moreover, it can be used to provide dynamic affordances and haptic feedback. Roudaut et al. [237] suggest for example to adjust the shape of a mobile phone according to the content it displays, by curling up the edges when performing a task where the device needs to be held with two hands.

2.2.2 Usage

Potential benefits

Interactive surfaces offer potential to improve human-machine interfaces with regard to different aspects.

Everything is an *intelligent* display Interactive surfaces can help us in making use of ambient intelligence – sensor technology, like it is already integrated in many devices, by drawing meaningful conclusions from the available data. The scenario of a supportive kitchen table by Xiao and Hudson [316], shown in Figure 2.8a, is an example of what might be possible in the near future. Everything the system requires are an object recognition system and the connection to different databases, in this case of recipes, ingredients and cooking instructions. It then recognizes which ingredients are available on the table, and provides tips what to do next. Intelligent objects around us can make the vision of ubiquitous computing, that technology will disappear into everyday objects [302], become real, and support us in daily tasks, without the need of explicitly asking a computer for it.

Seamless integration – *Everything* is a display Interactive surfaces can go beyond flat screens that are attached to an object to make it interactive. Interactive surfaces can enhance objects we already find in our daily life: the door of a refrigerator [173], advertising columns in public space [23], but also water surfaces [279]. Geller [85] showed how to transform any conductive surface into a touch-controlled surface, while others showed how to project simple graphical user interfaces (GUIs) on arbitrary objects, with input either realized through a hand-held device [255] or optical touch tracking [316]. All this does not require to introduce new devices, but the interactive surfaces can extend differently shaped surfaces of already available objects, thus seamlessly integrate into existing environments.

The desk in the *Starfire* concept video [282] contains both a horizontal digital table and a vertical display bent towards the user. It is an example for how an interactive surface in a workplace environment can integrate display portions of different orientation. This allows to change the organization of a digital document according to the context in which it is used: a user may prefer to read in the horizontal, but edit the same document in the vertical plane [313]; a curved desk can support the seamless transition between the different orientations. In remote collaboration settings, this configuration can also be used to integrate the dialogue partner in a more realistic way, by extending the own desk with a simulation of the counterpart on the opposite side of the desk as if he was sitting there [109, 21].

Digital information made tangible Sitting in front of a PC, data is often presented as numbers, strings or graphics on the flat and rectangle screen. There is no physical manifestation of the data but only a 2D representation of it. Mapping digital data to physical representations does not only make data easier accessible, but also more subconsciously understood. An early example is the *Dangling String* [303], a representative for calm technology that visualizes network traffic load with the movements of a string mounted in an office environment. Physical objects can also help to make digital data graspable [129] and give the user a feeling of what he or she is interacting with. This feeling is lost when interacting on a flat touchscreen that feels the same for everything that is displayed; however, it might be reintroduced by making use of non-flat interactive surfaces.

Classification

We use interactive surfaces in our daily life: they are integrated into smartphones, tablets, ATMs, coffee machines or embedded into the home for energy control. In those cases, interactive surfaces are often displays that are attached to objects, or the object itself is the display.

So far, interactive surfaces have been classified according to their size [302] and whether they are components of a larger object or the objects themselves [228]. There are more properties that can serve to classify interactive surfaces. Linked to size is *mobility*. Smart watches with interactive surfaces or smartphones can be taken along. Displays installed into larger objects, tabletops or especially architectural displays, are difficult to move. One could further classify interactive surfaces based on the *usage context*, similar to Weiser [302] who proposed tabs for identification and simple functionality, pads as scrap computers and boards to work together. Another aspect is the *input modality* that is used to interact with the object, from remote control with mouse and keyboard to direct touch and gestural control, and combinations of them. Hilliges et al. [111] have developed a physics simulation to allow for rich gestural interactions with objects close to the surface of digital tabletops. This can enhance direct touch interaction with object manipulation strategies users have collected with real world objects before. A further way in which interactive surfaces differ is how well they are integrated into devices or objects. The more seamless the integration is, the more the computer has disappeared. If we make use of existing surfaces, such as architectural facades, and enhance them with displays formed according to their shape, the *level of integration* is high. Similarly, tabletops, advertising columns or our own hands as in *OmniTouch* [94], are examples for well integrated interactive surfaces. On the other side, a smartphone that introduces a new device does not seamlessly integrate into the existing environment, nor do displays that are attached to existing devices such as coffee machines or other devices.

2.2.3 Technologies

To realize large and shaped interactive surfaces, different technologies can be taken into account for the display part, but also for interactivity.

Display technologies

The following section gives a brief introduction into different display technologies and their basic functionality. Understanding the different technologies is important to decide how well they are suited to be used for flat or non-flat interactive surfaces, and if prototypes can actually become products one day.

Background and terminology

A display can be *emissive*, which means that it is luminescent itself. This is the case for example for OLEDs, while other, *non emissive* technologies, such as LCDs or DMDs, require an additional light source that illuminates the pixel cells.

There are three different types of displays regarding the type of illumination. Objects and colors are perceived through the light that is reflected into the eye's receptors. *Reflective* displays do not have a backlight, but contain a mirror plane that reflects incoming front light through the pixel cells back to the user. This in turn means that if there is no front light, the display appears black. Watches often use an additional light emitting diode (LED) as front light to account for that. In contrast, *transmissive* displays use a backlight that illuminates the pixel cells from the back, often based on LEDs or electroluminescent films. *Transflective* displays combine these approaches and contain a half-transparent mirror between backlight and cells so that the front light is used to increase brightness [184].

Additional layers can be added to a display to improve image quality. Microprism structures can focus the emerging light to increase brightness for a certain viewing angle, or to deviate light in a different direction. This effect is used for stereoscopic 3D displays, where columns are pixelwise belonging to either the image for the left or right eye [57], or to separate images for driver and front-seat passenger [151]. Moreover, anti-reflectance (AR) coatings can be added to improve viewing angles [151], while diffuser layers are used to achieve a uniform distribution of the emitted light [317].

Display technologies for flat displays
So far, the trend of display research has been mainly to improve size, brightness and resolution. Several technologies, from CRTs to plasma displays and LCDs, represent the state of the art of established technologies.

Early computer screens were based on *cathode ray tubes (CRTs)*. They contain one or more cathodes that direct electron beams through a vacuum onto a screen that is (phosphorous-) coated. As a result, the picture is rendered line-by-line [184]. CRT displays provide good brightness values; however, they require more package space than modern flat panel technologies such as LCDs or OLEDs and have a limited life time due to the operation under high vacuum. They are only in rare exceptions used for in-car applications [200].

Plasma displays work in a similar way as fluorescent lamps: noble gas, such a Neon or Xenon, is activated between two glass layers. As a result, a phosphorous layer is emitting light that in turn illuminates color filters. Plasma displays can reach very low brightness values (i. e. good black levels); however, they have a comparatively high power consumption. Like CRTs, a low air pressure in required inside the cells; moreover, luminosity decreases over time and at least for early models, burn-in effects were a problem [184].

Liquid Crystal Displays (LCDs) make use of liquid crystal's light modulating properties. Controlled with electric current, it can change the polarization of light, and in combination with a polarization filter in front, influence if light passes through. Seven segment displays define fixed structures for the single cells of the LCD. In high-resolution displays, subpixels for different colors, that are later composed to image pixels, are organized in a matrix. Each subpixel is a separate cell between two glass layers that is filled with the liquid crystals. Transparent electrodes made of indium-tin-oxide (ITO) are attached to the glass plate to control resistor and thin film transistor (TFT) of each cell. Response times are between 1-10ms [184]. Compared to plasma displays, LCDs do not show burn-in effects and they are lighter and less expensive to produce. However, black levels are poor due to escaping light even with a perpendicular polarization. Moreover, it is not possible to bend them to a large degree.

Display technologies for non-flat displays
With the new fields of application of interactive surfaces, it will be required to have displays that are not flat but can be used to realize differently shaped display surfaces.

Electronic paper displays are mostly based on electrophoretic operation. They contain a layer with differently charged black and white particles encapsulated in microcapsules surrounded by a clear fluid (see Figure 2.10a). By applying a negative voltage to the front layer, white particles become visible, and vice versa, and form the image that is displayed. An active-matrix TFT backplane can be used to control single pixels [43], and a backlight can be added as required. On the positive side, electronic paper offers low power consumption, and a thin and flexible structure (see Figure 2.10b). However, so far there are only greyscale displays and the refresh rates are very low compared to other technologies.

Electronic paper is used for e-readers, such as the Amazon Kindle[12], and has been used for different prototypes investigating paper-like interaction. For example, *PaperPhone* [160] was

[12] `http://www.amazon.com/kindle` [cited 2013-11-26]

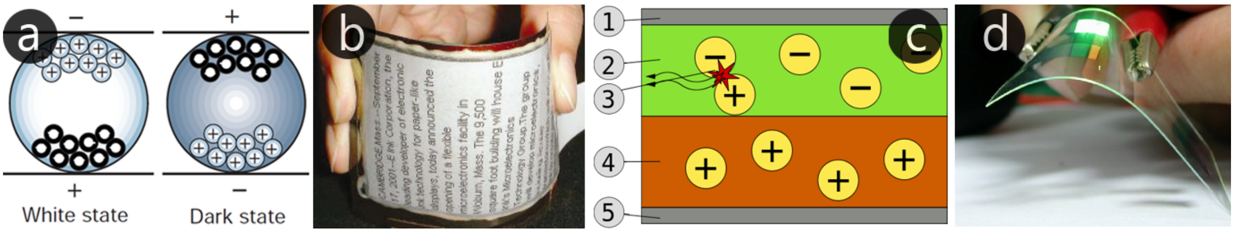

Figure 2.10: Overview of the technologies *electronic ink* and *OLED*. a/b: Electronic ink is made from microencapsulated electrophoretic material and allows small bending radii (figures taken from [43]). c/d: OLEDs emit light as a result of electron movements (1: Cathode, 2: Emissive Layer, 3: Emission of radiation, 4: Conductive Layer, 5: Anode) and can also be bent in one dimension[14].

built to examine different bending gestures, such as bending a specific corner to turn pages in a reading scenario.

Organic light emitting diodes (OLEDs) displays have emerged from anorganic *LEDs*. Those are widely used, in cars for example for warning lamps or to illuminate indications in the IC [184]. LEDs are available in different colors, for example white, red, green and blue, depending on the energy band gap of the semiconductor. They are cheap to produce, and have a good light efficiency in combination with low energy consumption [184]. They are based on semiconductor diodes that emit light by recombining layers with either an excess of electrons or electron shortage. Figure 2.10c depicts the different layers, and the transfer of atoms, creating radiation in the frequency of visible light.

The development towards OLEDs aims to replace the crystalline substrate with organic semiconductors which are based on polymers. Those are easier to manufacture, and make it possible to build very thin and flexible displays. OLEDs offer large viewing angles and good black levels; however, OLEDs are not, like LCDs, voltage-, but current-controlled, making the control more complex [184]. Limited lifetime, which becomes obvious as a flaw in color purity, was the biggest problem in the beginning. This is improving but still a topic of current research, as is the search for polymer materials and efficient manufacturing processes [138]. Samsung has released several TVs and smartphones based on OLEDs, with the model "Round" containing a statically curved front display[15]. *FlexCam* is an early prototype that uses a flexible OLED (FOLED) [54] equipped with camera lenses. The degree of flexion can be measured and translated into adjustments of the camera's field of view.

Projection displays are a further technology to realize very large, but also non-flat interactive surfaces. In comparison to direct-view displays that produce the image on the surface, a projection unit is placed in a certain distance to the surface that serves as the projection plane. In the case of front projection, the projector is placed over or in front of the surface, while for rear projection, the projection unit is behind the surface. The main advantage of rear projection is that the image

[14] © M. Eharris and RafałKonieczny. Both OLED figures are reproduced under a CC ASA 3.0 License.

[15] Jordan Crook: That Curved Display Smartphone From Samsung Is Real: Meet The Galaxy Round. `http://techcrunch.com/2013/10/08/that-curved-display-smartphone-from-samsung-is-real-meet-the-galaxy-round/` [cited 2013-11-26]

Figure 2.11: Using projection for prototypes. For *Xpaand* [147], a rollable display, a projected display was set up for early interaction user studies.

is not occluded when interacting on the surface. On the other side, it requires space to set up the projector in the projection distance and the projection plane needs to consist of material suitable for rear projection. Front projection can be realized on almost every surface, and is an enabler for Pinhanez' *Everywhere Displays* [208] vision to create ubiquitous graphical interfaces. Front projection with a pico projector can create mobile user interfaces on arbitrary objects [255].
The projection unit can be based on different technologies. *CRT projectors* use one or several small CRT units to generate the image. A lens is used to focus the image and enlarge it to the projection plane [30]. Like for desktop displays, projectors based on CRT have been widely replaced by new technologies, such as projectors based on liquid crystal. LCD projectors are transmissive and use polarizing LCD gates, often one for each color component, to control the backlight passing through. Using prism structures, the different colors are combined again. Liquid Crystal on Silicon (LCoS) projectors also use liquid crystal cells, but are reflective [30]. Due to their small package size, they are mostly used for pico projectors, but have also been applied in Google Glasses[16]. *Microelectromechanical systems (MEMS)-based projectors* such as Texas Instrument's digital light processing (DLP) technology uses digital mirroring devices (DMDs). Adjustable mirrors for each pixel in the displayed image reflect the light from the light source. *Lasers* can be used as an illumination source for the before mentioned technologies, or to create the image directly. The main advantage of the latter is that the output image does not need to be focussed on a certain projection plane but can display the image sharp in every depth plane. Three laser beams of the three primary colors are writing the image line-by-line [30].

Projection has been used in different prototypes for either static, flat or non-flat, and also flexible displays. It has been used for many setups of interactive tabletops [257, 312, 305] and to evaluate interaction concepts on flexible displays [147] (see Figure 2.11).

Input technologies

To make surfaces interactive, a sensor unit is required that detects user behavior. Thereby, intentional input can be detected and trigger a reaction.

Direct touch and touch gesture sensing technologies Interaction can be performed as direct touch or touch gesture input. There are different kinds of tracking mechanisms.

[16] `http://www.google.com/glass` [cited 2013-11-27]

Mavis Hong, Steve Shen: Himax reportedly lands LCoS solution orders for Google Glass. `http://www.digitimes.com/news/a20130307PD209.html` [cited 2013-11-27]

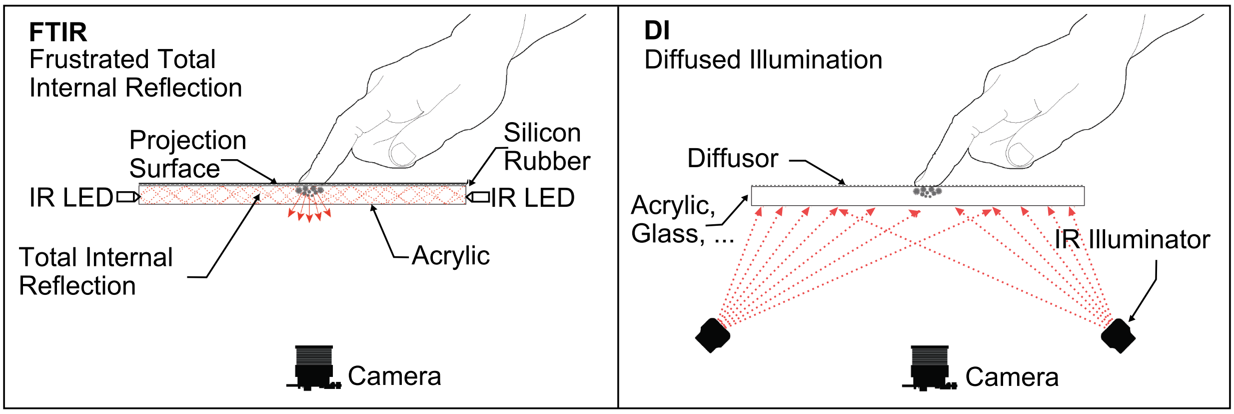

Figure 2.12: FTIR and DI setup for optical touch tracking based on IR illumination. The projector for the display is mounted inline with the camera below/behind the surface (figure taken from [257]).

Capacitive overlays are widely used for smartphones. The front cover is coated with a thin charge-storing layer. When a finger or a conductive stylus touches this overlay, capacitance and current flows change and the position of the touch can be calculated [170]. A problem is that skin contact is required, so gloves need conductive fingertips to enable interaction. A similar approach is to measure different frequencies of an object's overall capacitive output as in *Touché* [253]. Different hand positions and postures on an object's surface can be differentiated without the need to add an additional sensing layer. This can be realized by embedding a single sensor into the object.

A technology often used in ATMs is *resistive* touch. On the screen surface, two layers with conductive coatings are separated by invisible separator dots. An interaction causes pressure on the surface, so that the two layers touch each other, and the circuit is closed. The resulting change of current can be used to locate the touch point [170]. Further technologies are *inductive* touchscreens, or screens based on *acoustic waves* or *infra red (IR)* in the cover layer [170]. A way to measure bezel-tapping to enhance touch tablet interaction is to use the *accelerometer* data. This can be used to interact with a sleeping device since the accelerometer consumes less energy than the capacitive sensor [264].

Furthermore, touch points can be detected *optically*. A camera can be mounted above or laterally to measure the distance between fingertip and object surface [94]. Especially for rear projection systems, optical touch tracking based on IR illumination is common and easy to set up. Two widely used mechanisms are based on frustrated total internal reflection (FTIR) and diffuse illumination (DI) [257] (see Figure 2.12). For both, a camera with an IR filter is placed in the back of the screen. Using FTIR, IR is emitted into the front pane from LEDs around its edges. The IR keeps traveling inside the material as long as the refractive index of it is larger than any touching material. A compliant layer with a higher refractive index, e.g. silicon, is applied to the front with a small air gap, so it does not touch the IR layer permanently. When the screen is touched with a finger, the air gap is closed, IR escapes, reflects to the back and can be captured by the camera. The camera image can then be processed using computer-vision algorithms and visible points can be mapped to screen coordinates. Using DI, the IR LEDs illuminate the area before the front pane. IR is reflected by fingers or other objects touching the screen, and with less intensity, also above the screen. As before, the camera captures those reflections and calculates the touch position.

Freehand gesture sensing technologies To capture interaction in front of a surface, *IR distance sensing* [171] or, more advanced, *capacitive sensing* [11] has been used to detect the approach of a finger or hand. This simple gesture can be used to control a reduced set of functions [171], or to increase the information density in more complex interfaces [11], for example by displaying more information as a hand comes closer. Camera-based depth tracking can been used to detect touches and hovering actions [100], but also more complex gestures [111].

Attaching control elements To build a bridge between traditional interfaces with knobs and interactive surfaces such as tabletops, haptic control elements can be added to the surface. Those can be either screwed or glued permanently, or be flexibly attached to the surface using adhesive material as shown with *Vertibles* [110]. Using magnetic controls [304], electromagnetic fields can be used to rearrange physical controls depending on the current use case. Fiber optics can be used to lift an image displayed on the surface to the top of an attached element such as in *Lumino* [18]. There are different ways to recognize the interaction that is performed with such an element. On rear projected tabletops, optical marker recognition has been early introduced for the objects that were used on the *reacTable* to control music replay [136]. Similarly, it served to detect the interaction with *SLAP widgets*, which were designed to mimic keyboards, switches or rotary controllers on the *BendDesk* [307]. Markers for resistive sensing have been introduced with *Geckos* [167]. For capacitive touch surfaces, marker recognition can be easily implemented using conductive ink [311].

Commercial products that make use of additional control elements are for example the Neff TwistPad[17] that is magnetically attached to a suitable hearth. It can be turned and pushed towards a specific direction to select a hotplate, while it can also be taken off for cleaning. AppMates[18] are toys to be used with an iPad to control a racing game. They are based on capacitive sensing where markers on the bottom side of the devices are recognized just like fingers touching the screen; the application expects touch points in certain constellations and interprets them accordingly.

2.2.4 Conclusion

Interactive surfaces can enhance our surrounding by presenting information on adaptable digital displays. By using them, we can access information through objects of our daily life, always choosing the one that is best suited in a specific context. Ideally, the computer behind the objects should be as invisibly as possible.

With a PC on our desk, we have defined input and output devices. We have a precise pointing device and a keyboard that supports text input by providing us with familiar button feedback. It is not clear yet how we will be able to communicate with arbitrary objects. How can I tell my coffee table what I want? Touch is a solution that works for many kinds of surfaces, but those lack

[17] `http://www.neff.de/twistpad` [cited 2013-11-28]

[18] `http://www.appmatestoys.com/` [cited 2013-11-28]

tactile feedback to confirm if an input has been accepted or not. Attached physical controls as well as display and input technologies for non-flat interactive surfaces are promising directions to ease the interaction. Sections 3.3 and 3.4 will provide an overview of research on the interaction with interactive surfaces according to the relevant aspects for this thesis defined in Section 3.2.

Essence Interactive surfaces have been applied in tabletops and wall-sized displays, but are predominantly used in smartphones and tablets. Interaction with interactive surfaces has evolved from cursor-based remote control to direct touch interaction, and gesture-based approaches are increasingly developed.

Chapter 3

The Next-Generation Cockpit?

Large and Shaped Interactive Surfaces in the Car

The previous chapter has given an overview of requirements and challenges when designing automotive user interfaces. Moreover, the field of interactive surfaces has been introduced. Those fields have already begun to merge. Interactive surfaces have been introduced to the car and there are indicators that this development will be continued.

To explore the potential of interactive surfaces in the car, this chapter provides an overview of related topics when designing interactive systems, and substantiates the focus of this thesis. Furthermore, research in the fields of large and shaped interactive surfaces is presented which can inspire the design of automotive user interfaces. The following chapters will be based on this.

3.1 Interactive surfaces for automotive user interfaces

Car cockpits have changed considerably from the early beginning of automobiles to the latest models, and by that time, interactive surfaces have moved into automotive user interfaces. Compared to conventional buttons, they have advantages regarding wear and hygiene as no moving parts can break and there are no joints or other openings in which dirt could accumulate. Research in related fields and the direction given by concept cars can inspire the speculations on the future development of car cockpits.

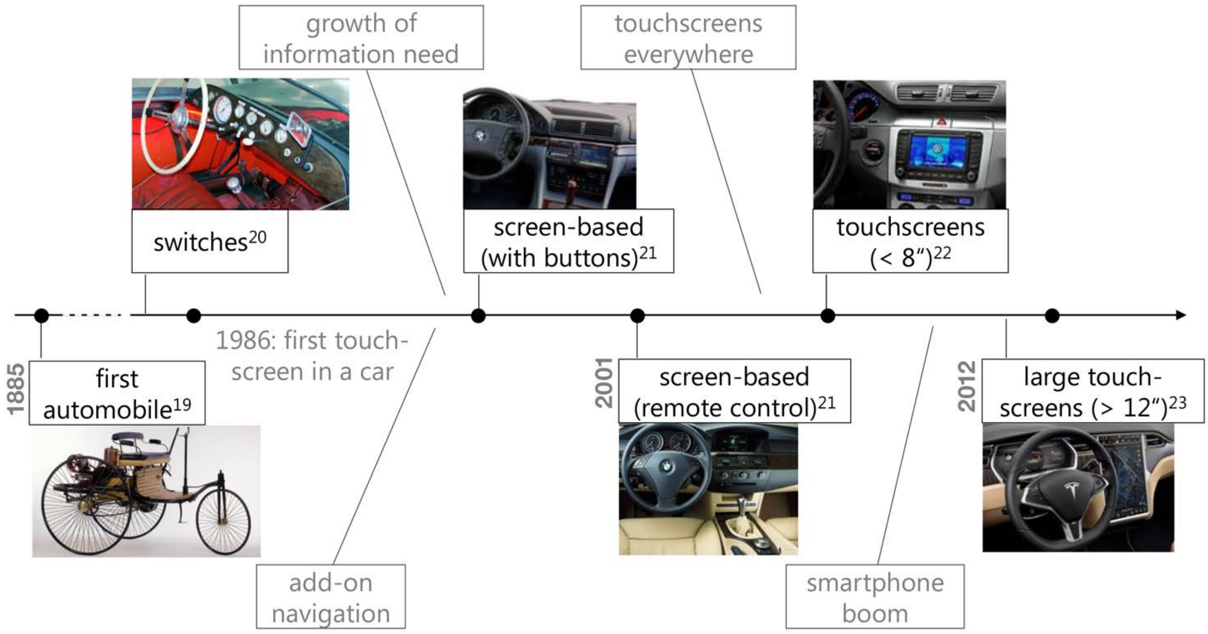

Figure 3.1: Evolution of interactive surfaces in cars and influencing factors. Details can be found in the text.

3.1.1 Evolution of automotive cockpits

Automotive cockpits have evolved over time – from the first automobile by Carl Benz in 1885[19] which looked similar to a horse-drawn-carriage, to the cars that are on the road today (see Figure 3.1). What they have in common is the driver-orientation towards the front to monitor the traffic situation, with all controls in direct reach – may it be a driving stick as in 1885, the steering wheel, or controls for additional functionally that have, bit by bit, found their way into the car. The racing car's cockpit by VEB from 1954[20] is an example for the use of switches and the typical direct mapping of knobs to functions. In 1986, the Buick Riviera featured an early touchscreen interface called "Graphic Control Center" [200]; however, it was abolished only some years later and replaced by hardware switches again.

In the following years, functionality grew rapidly. On the one hand, this was influenced by the increased use of hand-held navigation devices people brought into the car, and which car manufacturers soon built in themselves. On the other hand, the distribution of internet access raised the overall (perceived) information need. To cope with that growing amount of functionality where a direct one-to-one mapping of controls to functions became impossible, more and more cars got equipped with screens. The analysis of an automotive trade show in 2007 [146] showed that more than 70% of the exhibited cars already had a built-in screen. Those were either controlled with buttons along the screen's border (e.g. BMW 7 series of 1993[21]), with a remote controller

[19] `http://www.daimler.com/dccom/0-5-1322446-49-1323352-1-0-0-1322455-0-0-135-7145-0-0-0-0-0-0-0.html` [cited 2013/12/01]

[20] © Photo by Ralf Christian Kunkel.

[21] © Photo by BMW Group.

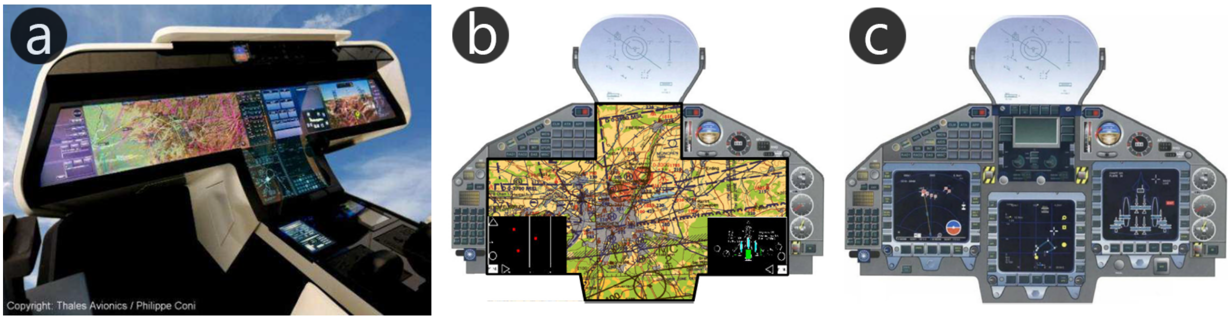

Figure 3.2: Research in aviation investigates the replacement of several small screens with one large-area screen. a: ODICIS single display cockpit mock-up [20][24] b: Cockpit with three head-down displays based on the Eurofighter Typhoon [141] c: Cockpit integrating the *Panoramic Display* by Kellerer [141].

(introduced 2001 in the BMW 7 series[21]), or, with a growing amount, by touch, for example early in the 2005 VW Passat[22]. Thereby, manufacturers aimed to provide full flexibility regarding the offered functionality and content, but also to follow the trend of CE devices which had discovered (or created) the ease and joy of use of direct manipulation on interactive surfaces. A recent development is that the utilized touchscreens are growing in size, with the so far largest 17" touchscreen in the Tesla Model S[23] released in 2012.

3.1.2 Next steps in automotive cockpit design

We will not know what future cockpits look like until they are released. However, research on other means of transportation as well as latest concept cars presented by car manufacturers at motor shows give an outlook of how automotive user interfaces might evolve.

Cockpit development in aviation and transportation

In aviation, where pilots have to cope with a variety of control and surveillance tasks, researchers have explored the potential of screen based cockpit solutions (see Figure 3.2). The *ODICIS* project (One Display for a Cockpit Interactive Solution) focused on the technical feasibility of large, seamless and curved displays with the goal to support architecture flexibility and information continuity [20]. The final result, a rear-projection prototype based on five projectors, equipped with optical touch tracking, was presented at the 2011 Paris Air Show. In high-workload environments such as fighter jets, it is important to provide an easy way to interact with the machine interface. *PanDis* (Panoramic Displays) [140], a research project of EADS, investigated input modalities when replacing the existing separated displays and switches of an Eurofighter Typhoon with one large screen. The goal was to be able to flexibly integrate new and improved

[22] © Photo by Volkswagen AG.

[23] © Photo by Tesla Motors.

[24] With kind permission of Loïc Bécouarn © 2012

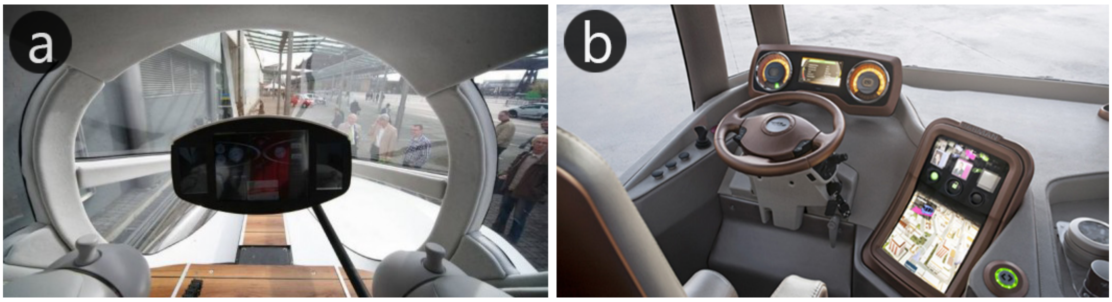

Figure 3.3: Transportation concepts a: TUM InnoTruck [3] b: Rinspeed microMAX[25].

functionality to support the aviator. One interface concept extended the "Big Picture Cockpit" [2] idea. It is based on overview maps that can be enhanced with further complementing information windows, and aims to raise pilot awareness [141]. Different input modalities for such a cockpit are for example direct touch and remote trackballs. Touch was shown to foster increased input speed and decreased subjective workload [140] as well as increased secondary task performance and decreased sensibility to task interference [64] compared to the trackball solution. On the other side, selected results show that touch input with an outstretched arm can lead to operating errors in the final targeting phase, especially when visual attention is caught by a high workload primary task [140]. Overall, this leads to the final conclusion that a combination of different input modalities is most suitable for the varying existing workload situations [140] when operating on a large single-display cockpit.

In the context of large road vehicles, *Innotruck*, a research project of 2012 by the Technische Universität München [3] presents a newly designed truck driver workplace. The interface incorporates a large screen (Figure 3.3a) and aims to make use of the flexibility of its digital presentation of information. To prevent fatigue though information overload, content and information density are adjusted to the current status of the driver. Similar, Rinspeed and Harmann presented a cooperative concept study, *microMAX*, at the Geneva Motor Show 2013[25]. The 19” screen is based on rear projection and supports interactivity through touch input. It supplements a digital instrument cluster (Figure 3.3b), to support parallel access to navigation, infotainment and community functions like the search for passengers.

Presented concepts for passenger cars

In the last years, there have been a number of concepts presented by car manufacturers integrating new kinds of screens in passenger cars (Figure 3.4).

In 2011, there were several concept cars showing new form factors for displays to fit the geometry of existing cockpits. Daimler’s *F125!*[26] integrated a touch and gesture controlled, non-rectangular display in an area next to the driver, on the right side of the instrument cluster. The

[25] "microMAX" - das vernetzte Schwarm-Auto. `http://www.rinspeed.eu/aktuelles.php?aid=13` [cited 2013-10-13]

[26] F 125! `http://technicity.daimler.com/f125/` [cited 2013/12/01]

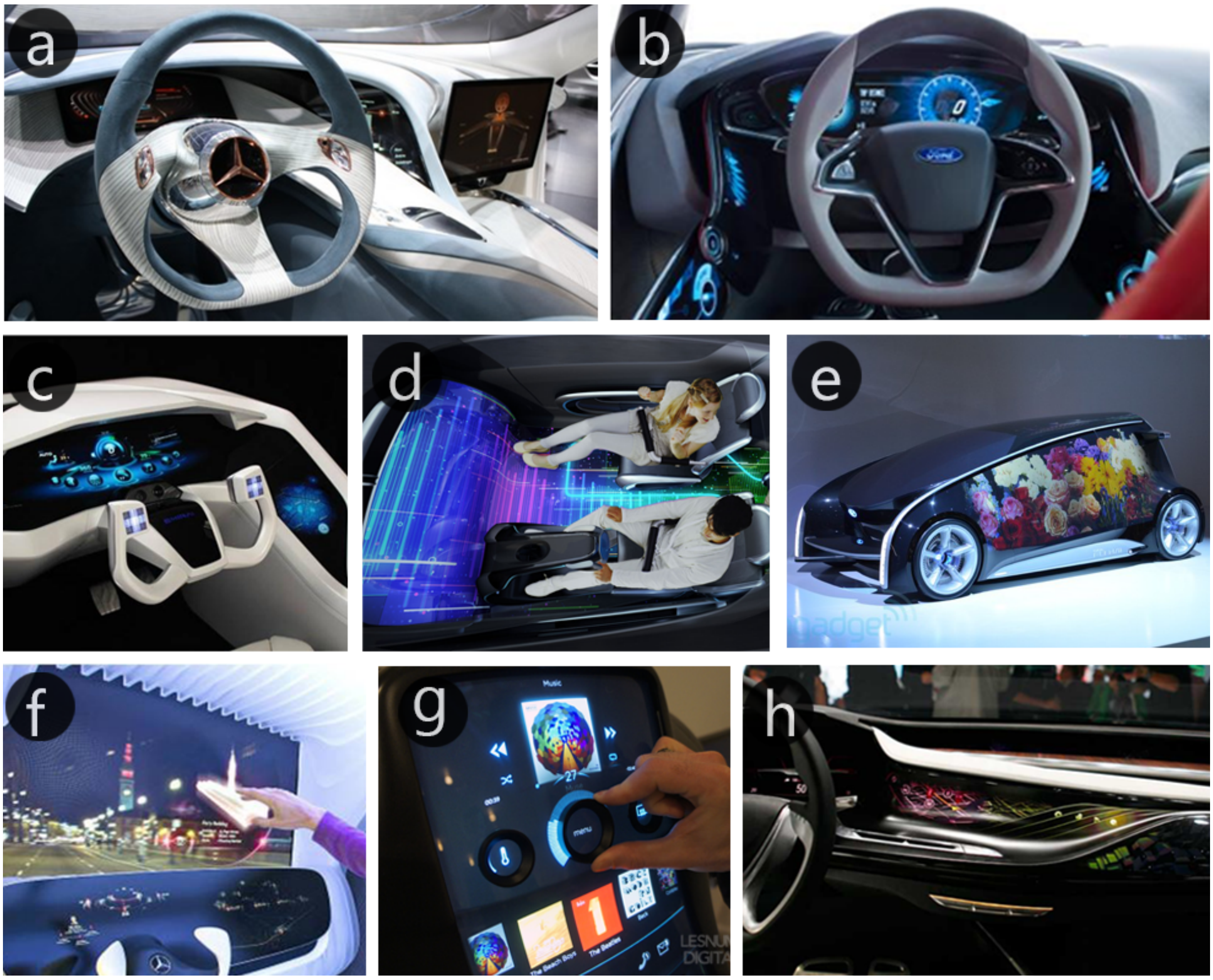

Figure 3.4: Concept cars by car manufacturers and suppliers. a: Daimler *F125!*[26] b: Ford *Evos*[27] c: Mitsubishi *EMIRAI*[28] d/e: Toyota *Fun Vii*[29], interior and exterior view f: Daimler *DICE*[30] g: Texas Instruments interactive display[31] h: Opel *Monza Concept*[32]. Details can be found in the text.

concepts Ford *Evos*[27] and Mitsubishi *EMIRAI*[28] went one step further. Both showed even larger, seamlessly connected display areas all around the driver workplace. Toyota showed *Fun Vii*[29], incorporating large displays not only in the interior, spanning over the whole cockpit and floor area, but also on the exterior surface, allowing to change the cars appearance completely. In 2012, Daimler presented *DICE*[30], a cockpit with a flat display merging into an augmented windshield, creating a large, gesture controlled interactive area in front of driver and passenger. A feasibility

[27] `http://www.ford.de/Pkw-Modelle/Produktneuheiten/Ford_Evos_Konzept` [cited 2013/12/01]

[28] Randolph Jonsson: Mitsubishi's concept EMIRAI driver interface system. `http://www.gizmag.com/mitsubishi-concept-emirai-driver-interface-system/20801/` [cited 2013/12/01]

[29] `http://www.toyota.com/letsgoplaces/fun-vii-concept-car/` [cited 2013/12/01]

[30] Johann Jungwirth: Die "Appification" des Automobils. `http://technicity.daimler.com/ces2012/` [cited 2013/12/01]

study of the technology required to realize such concepts was presented by Texas Instruments[31]. They presented a rear projection prototype which enabled touch and touch gesture functionality. Moreover, optical tracking allowed to integrate hardware control elements into the display area. A recent development in 2013 was the *Monza Concept* by Opel[32], which showed a wide projection integrated into the cockpit combined with decorative physical strips. In this way, the display weaves even better into the cockpit architecture, and at the same time allows to greatly change the appearance of the cockpit.

Essence The evolution of automotive user interfaces and the presented concepts for cockpits in cars and other transportation domains indicate that touchscreens will play an important role in the future. We see a trend of growing display sizes and more seamlessly integrates interactive surfaces. Therefore, the two aspects *largeness* and *size* will be investigated in detail in the subsequent chapters.

[31] Romain Thuret: Texas Instruments Invents the Dashboard of the Future. http://www.digitalversus.com/texas-instruments-invents-dashboard-of-future-n29368.html [cited 2013-11-05]

[32] http://www.opel.de/opel-erleben/ueber-opel/aktuell/2013/07/opel_news_monza-concept.html [cited 2013/12/01]

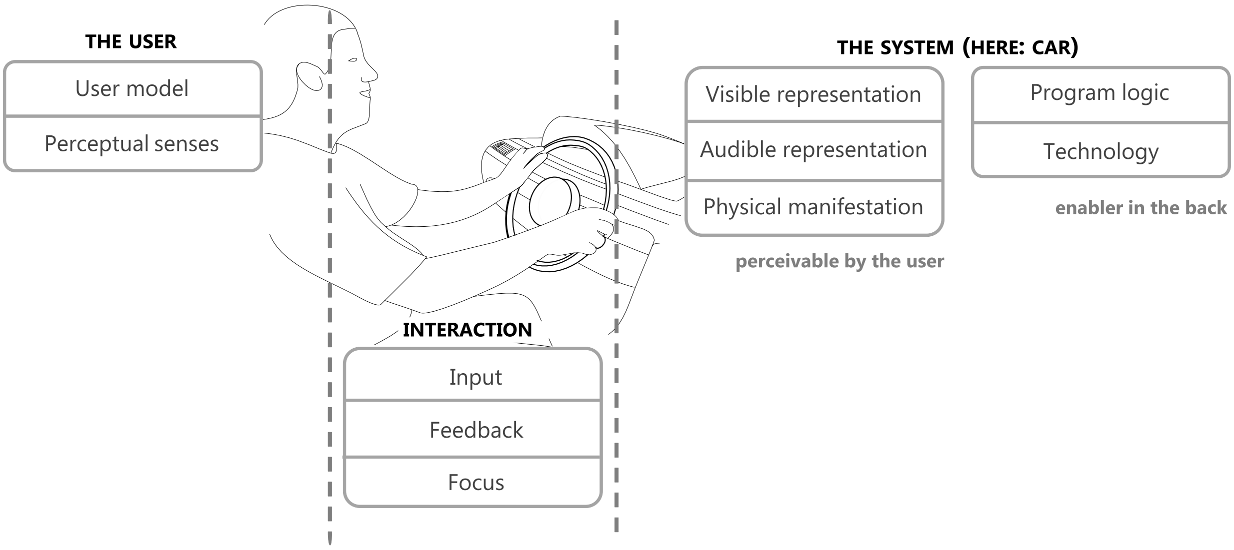

Figure 3.5: Design space of interactive systems. Between the different parties, user and system, the interaction takes place (figure based on Verplank's interaction loop [290]).

3.2 Design space

The last section has given an impression of what we can expect regarding the future development of automotive cockpits, especially regarding touchscreen integration. To be able to classify the work of this thesis, strengthen its focus, and set the boundaries to other work, the following section presents the design space for the development of interactive systems. Different components influence what interaction with the infotainment system looks like. Afterwards, several taken restricting preconditions as well as the focus of this thesis are presented.

3.2.1 Components of interaction design

Inspired by Verplank [290] and the ACM SIGCHI Curricula for Human-Computer Interaction [12], Figure 3.5 depicts the main components that need to be taken into account when designing an interactive system such as an infotainment system in the car.

On the left side, the *user* has a user model of how he or she thinks the system is intended to work. This is shaped by prior experiences and expectations, intentions and goals. Furthermore, there is a broad but also ergonomically limited range of perceptual senses: the user can see, hear and feel the system.

On the other side, there is the *system*, for example the car and its built-in or brought-in devices. As the counterpart to the user's mental model, it realizes a certain program logic that defines its functionality and ways of operation. It is built based on a certain technology that also influences the capability and appearance of the system. This can include display technologies, but also network connectivity or computational power. Apart from such core components, there is the part that is visible to the user. This refers to the human senses: the system can be visually, audibly and haptically perceived.

In-between, *human-computer interaction* takes place. In the one direction, the user can be involved with the system and perform input; for this purpose, the system needs to communicate its affordances to let the user know how it can be manipulated. In the opposite direction, the user receives feedback from the system when it reacts to the manipulation. Interaction can be performed explicitly for example by switching a button, or implicitly for example by approaching a door that opens automatically. Moreover, it can be in the focus of attention, or be treated as a secondary task.

3.2.2 Preconditions assumed for this thesis

There are several preconditions that are assumed for this thesis when developing novel interaction concepts based on interactive surfaces. In the following, the decisions for those are substantiated with findings from the previous sections and further related work.

Interaction while driving – Focus on avoiding distraction

The first determining factor is that interaction needs to be possible while driving without impacting driving safety. Therefore, requirements for automotive user interfaces need to be taken into account. The user needs to be able to perform interaction concurrently while driving, preferably eyes-free, and while allowing for interruptions in situation when critical events occur. As a consequence, the focus of evaluations of interaction concepts should be on the effect on distraction from the primary driving task. The NHTSA [193] as well as most other institutions that publish guidelines and standards on automotive user interfaces, claim three main categories:

Avoiding *visual distraction* particularly aims at reducing the amount of time when glances are averted off the street, since critical events that require immediate reaction could remain unnoticed. The goal is to not make the interaction visual distracting, which can be evaluated by measuring the number and duration of glances as well as by assessing the subjective impression of the user.

Manual distraction is met when the driver is not able to keep the hands on the steering wheel. It is only acceptable for a certain time, and there should never be more than one hand off the steering wheel, at least as long as fully automated driving is not available. To test for manual distraction, one can measure secondary task completion time while observing the hands' behavior.

Mental distraction can reduce the ability to monitor traffic and react to changes appropriately [119], so it is important to keep the workload of secondary tasks low. Mental distraction can be assessed by measuring driving performance as well as secondary task performance, and also by collecting feedback on the subjective impression of the workload level.

Digital content presentation – Enable customization

The second assumption that is taken as a precondition is that instead of relying on hardware switches and permanent mappings of control elements to functions, the next-generation of user interfaces will by an increasing share be presented on adaptable digital interfaces. Digital interfaces as an enabler for customization are not a precondition in the sense of the first one, but strengthen the need for the development we saw in Section 3.1.

Customization takes place in many domains. We can customize ergonomic settings in our desk environment by adjusting the height of the table to our body height. Similarly, we adjust tools or bags to fit our ergonomic conditions and to make them comfortable to use. In a digital environment, an ergonomic adjustment might be to put functions that are often used at positions that are easy to reach, for example at the top of a drop-down menu such as in split menus [70] or in the corner of the screen as realized in Apple's *Hot Corners*[33]. Regarding the visual and functional design of products and user interfaces, Marathe [178] found that different categories of individualization address different psychological needs. She distinguishes a) customization of the look and feel, which increases the sense of identity, and b) customization that focuses on functionality issues, which in turn increases the sense of control. Regarding the first category, this includes the adjustment of color themes, or putting a personal plate on a smartphone. The second category is more challenging: it requires to be able to make changes in content (e.g. what widgets are displayed on the desktop) and procedures (e.g. how often are emails fetched from the server). All those decisions can be adaptable and made by the user, or adaptive and adjusted automatically by the system (or a combination of it) [36]. No matter what strategy is chosen, the customization of a product can not only make the usage easier but also change, and possibly improve, the user's sense of identity and control.

In the car, the main customization today takes place when ordering a car: the customer can choose between different engines, colors, and other special equipment to be delivered. Equipment packages or trim levels aim to support the customer by offering a preselected choice fitting specific customer groups. Ergonomic changes can be made regarding seat, mirror and steering wheel positions, and a number of live functional adjustments are possible (e.g. switch on/off driving assistance systems). However, often it is not possible to customize the access to functionality: there are fixed sets of buttons to control a predefined set of functions (e.g. driving assistance buttons, climate control buttons). An exception are buttons that can be dynamically assigned such as the "functional bookmarks" by BMW[34] that allow to have hardware keys to access arbitrary functions of the infotainment system.

Only recently, it has become possible to upgrade functionality through app stores at any time after purchase. Being able to customize the functionality when sitting in the car will raise the need to also customize the way to access it. A digital interface can offer the required flexibility. The growing amount of functionality has already led to the introduction of screens (see Section 3.1.1) that present information depending on what the user has customized and currently selected.

Direct interaction – Bridge the articulatory distance

As a third precondition, all considerations of interaction concepts shall be based on direct interaction with the environment.

[33] `http://www.apple.com/findouthow/mac/#quickscreensaver` [cited 2013/12/01]

[34] `http://www.bmw.com/com/en/insights/technology/technology_guide/articles/functional_bookmarks.html` [cited 2013/12/01]

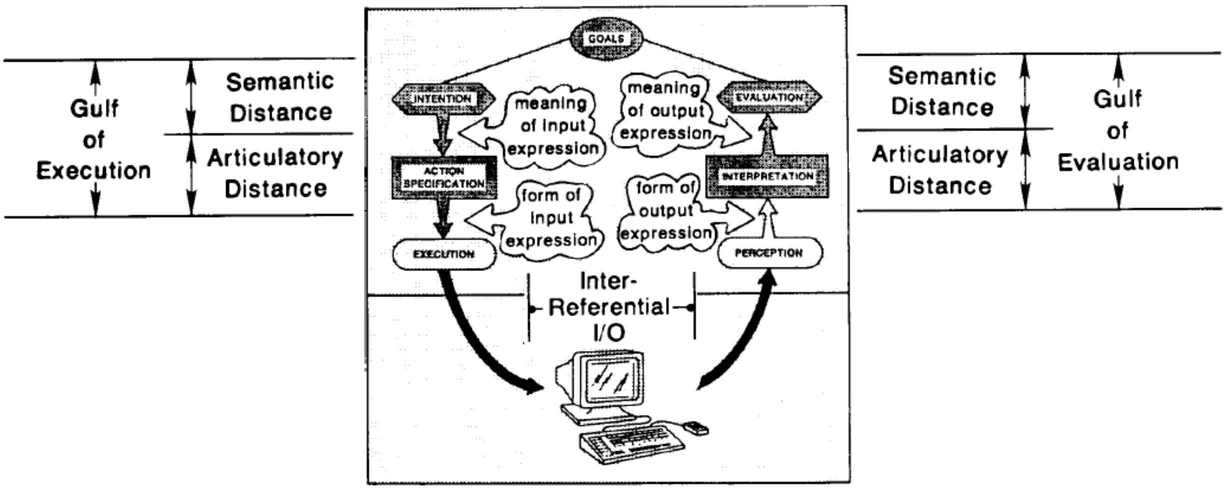

Figure 3.6: Performing an activity ranges from intention to evaluation. Therefore, the user has to overcome both semantic and articulatory distances (figure taken from [121]). Details are explained in the text.

Often, direct interaction and manipulation is equated with touch interaction; however, gestures such as pointing or grasping for something can also be considered as direct when the user can indicate directly which object or location he wants to interact with. The main difference between direct touch and direct gesture interaction is the immediate feedback: the user receives direct tactile feedback when the finger touches the screen's surface, while gestural interaction might benefit more from kinesthetic perception.

Shneiderman [265] first came up with the idea of *direct manipulation* to improve the interaction with interactive systems. He did not refer to touch or gesture input, but claims that, instead of abstract syntax, continuously visible representations of objects should represent the system status. Those are directly manipulable, such as clickable buttons that imitate the behavior of real buttons. As a result, it can become immediately visible to the user what operations can be performed, what impact they will have, and how operations can be reverted.

Direct manipulation can help solving the problems that arise when a user wants to achieve a certain goal. On the input side, he needs to find out how to manipulate the system to achieve the goal (*gulf of execution*). There are two steps, depicted in Figure 3.6, that need to be performed here: to cope with the *semantic distance*, one needs to find out how the intention can be mapped to an expression, i.e. needs to translate the goal into a certain action. After that, the *articulatory distance* needs to be overcome and the expression needs to be translated into a physical form or action (i.e. the mouse needs to be moved and clicked). On the feedback side, it is necessary to evaluate if the action was successful. This leads to the *gulf of evaluation*. One needs to follow the changes initiated by the action (*articulatory distance*) and compare the result to the initial action (*semantic distance*) [121]. Direct manipulation can support to overcome the articulatory distances. If one needs to select a certain item on the screen (execution), and it is possible to directly click or point on it instead of typing some abstract command, there will be less effort to achieve this task. On the other side (evaluation), if the action causes an object to change for example its color instead of displaying a color code, this directness can support the understanding.

Overall, Hutchins et al. [121] state that the "natural translation of intentions to actions" and the "immediacy of feedback" of direct manipulation has advantages when it comes to comprehensibility of the interface. Users can see immediately how their actions affect an object [45]. It also helps users to feel in control as they can predict what results their actions will cause [265]. Direct touch interfaces can make use of existing knowledge from mouse interaction (i.e. buttons can be clicked) [93]. With an increasing distribution of touch-based smartphones and tablets, users will potentially have an increased set of touch gestures extending the nowadays widespread zoom and swipe gesture. Direct manipulation touch interfaces do not require any additional remote controller such as the mouse for PC users or the multifunctional controller for users in the car. There is no need to switch the input modality or the operating mode when performing different tasks such as navigation or selection in a list and x/y positioning on a website or map. However, simplicity can also have drawbacks regarding the expressiveness of the interface or make things more complicated, for example when direct pointing at an object is not possible.

Direct interaction in the car In the context of the car, especially when talking about touch interaction, regulations can cause further issues. The area to display content should be close to the line of sight, preferably within a 30° range [47], but at the same time it is required to have all controls in a distance that does not require to lift off the shoulder from the seat. This results in an ergonomic conflict of interests; when a screen is mounted high enough to be in the designated 30° area, it might cause fatigue for the interacting arm [34]. The lack of meaningful tactile feedback on flat touchscreen can lead to visual distraction from the road when targeting interactive areas. Further drawbacks of direct interaction are that the screen can get polluted from dirty hands leaving smudges [296] and that intended objects may be occluded by the interacting hand [248], causing even more visual distraction.

Overall, the use of direct (touch) interaction seems to be unsuitable for the use in automotive interfaces. However, they are already available and deployed in the market and there has been research which successfully applied approaches to overcome some of the problems (see Section 2.1.3). It is assumed that the trend of direct manipulation instead of indirect interaction through remote devices will continue. When designed accordingly, advantages can potentially outweigh the drawbacks, so the idea of direct interaction will be integrated in all concepts.

3.2.3 Problem definition

Interactive surfaces have already been applied in the car, and this usage is likely to increase in the future. It is, however, not yet clear how this medium can be controlled while driving. Through the advances of size and free-form properties of display technologies, new physical manifestations of interactive surfaces can become possible. In contrast to the small and medium-sized flat touchscreens of today's infotainment systems that are based on simple touch input, new form factors can for example make use of the sense of proprioception or our ability to perceive surface structures.

Analysis of interaction

The direct interaction with an interactive surface can be subdivided into several steps. This analysis focuses on interaction of low complexity according to Harvey [97], so the selection of an item such as a button representing a function or menu entry is examined. This can then be composed to more complex tasks such as text entry. Such a discrete selection [97], also called pointing task [236], has for example been modeled by Fitts' law [71], which shows the dependency of interaction time on target size and distance.

System From a system perspective, the interaction can be described by Buxton's model of graphical output [40]. It originally described three states for the interaction with a graphics table and a stylus. First, the input device is out of range for the tablet (0). When it gets in range, its position can be actively tracked (1). Finally, an additional signal, for example extra pressure, triggers an action (2). For direct input devices such as touchscreens, *State 1* is bypassed as the system does not know where the interacting finger is positioned before the actual contact. As a result, the model is reduced to the two states depicted in Figure 3.7.

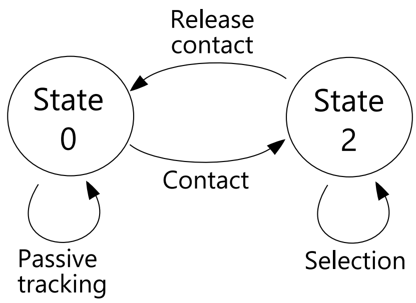

Figure 3.7: Buxton's state model from a system perspective (figure adapted from [40]).

User On the user side, there are several steps that do not have a counterpart on the system side. As a result, they can hardly be supported and require increased user attention.

From an *idle* state (0), the user passes different motor states, depicted in Figure 3.8. Pitts et al. [211] distinguish between *search* and *selection* phases when interacting on a touchscreen. The search phase can be split up in two steps [63]. First, the user has to visually explore the screen to localize the interactive element that has to be touched (1). As a second step, the interacting finger has to be positioned above the screen (2). Swette et al. [277] call this the goal-directed reaching movement, which includes both coordination and motion. As a result of the reaching movement, the finger touches the screen (3). The selection phase contains an additional step after the selection. As a result of the interaction, the user can feel the haptic barrier when touching the surface but does not get a haptic indication if the action was performed successfully or not. On traditional flat touchscreens, feedback is therefore provided visually, for example by animating a button to look as if it was pushed down. There are further approaches such as movements of the surface in z-direction [229], or vibrotactile feedback [212] that can add more expressive feedback. Those require complex mechanics and cause the whole surface to be actuated.

Visual attention is required for several of the steps. Table 3.1 sums up the interaction steps and how they demand visual attention. Harrison and Hudson [95] distinguish glances required for the

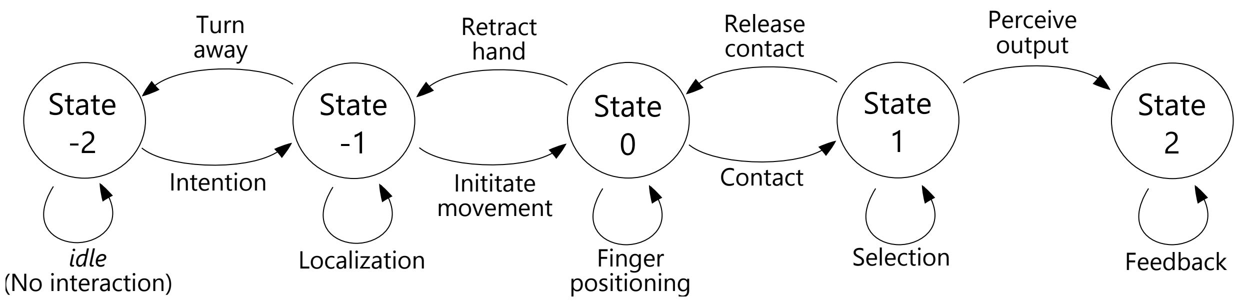

Figure 3.8: State model from a user perspective according to related work. Details can be found in the text.

interaction: *search glances* are used in the localization phase. Because normally every contact with the screen triggers an action, further *confirmation glances* are needed to confirm the finger position before finally selecting a target item and after the action has been performed.

Phase	Task	Description	Action	Visual
		Idle position		-
Search	1) Localization	Explore the screen	Hand in idle position	x
	2) Positioning	Coordinate the hand movement	Hand positioned, then hovering over the screen	x
Selection	3) Input	Perform selection	Hand is touching the screen	-
	4) Feedback	Perceive system output	Hand is moving back	x

Table 3.1: Model of direct interaction and the example of selecting an item on a touchscreen.

Focus of this thesis

This thesis aims to explore the interaction potential that opens up through the physical manifestation of interactive surfaces in the car, and how specific characteristics of the two emerging properties *largeness* and *shape* can be used to influence and improve the interaction. Figure 3.9 presents an overview of the topic's classification in the context of the design of interactive systems, under the three preconditions *driving*, *digital* and *direct*.

Interaction concepts and the current status of in-car systems have been described previously in Section 2.1.3 and 3.1.1. Most approaches focus on visual and auditory aspects. The physical manifestation of the interface has only been investigated in the course of traditional knob design but not in combination with touchscreens; haptic feedback for touchscreen has focused on vibrotactile output. Therefore, there is a lack of research in the area of haptic feedback through

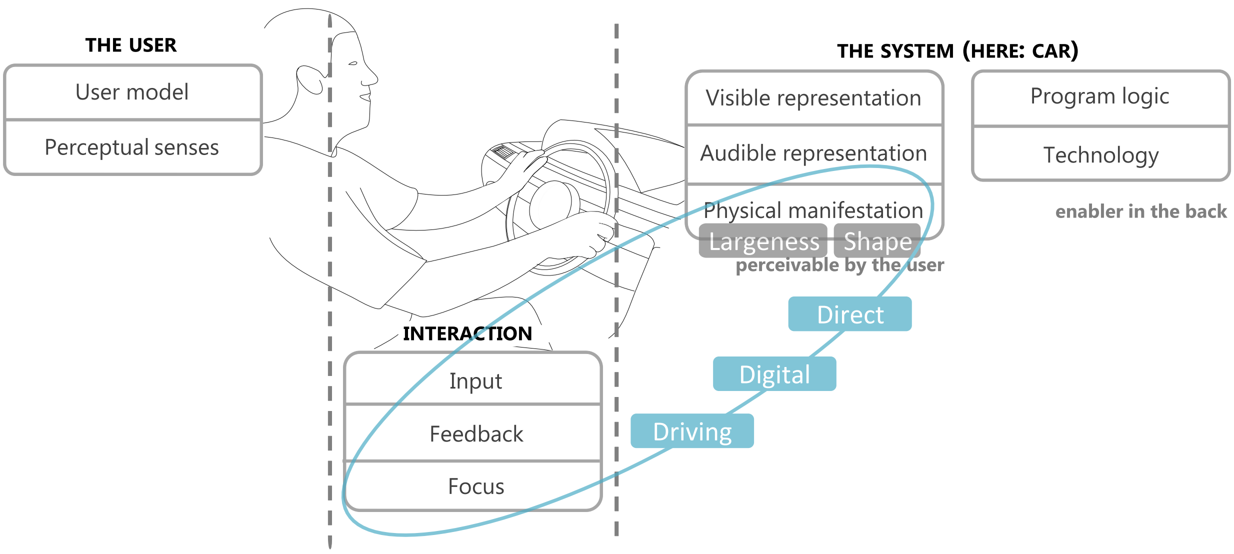

Figure 3.9: Design space of interactive systems (figure based on Verplank's interaction loop [290]). This thesis focuses on the effect which the physical manifestation of the system can have on the interaction.

the physical manifestation of touchscreens in combination with direct touch. Visual and auditory aspects of the interface can and must not be neglected when developing in-car systems; for prototypical realizations, visual and auditory feedback will be realized as necessary. However, as the main goal is to reduce visual distraction, concepts will concentrate on the physical properties of the interface. Explorations of those will take place in close coordination with users, to observe how input and feedback are performed and understood. Program logic and technology that only enable well-usable interactive systems will be described as part of prototypes that realize specific characteristics of the physical manifestation.

In the following, Section 3.3 and 3.4 will present related work on the use of the two properties *largeness* and *shape* for interactive surfaces. Since there has not been extensive research on the use of large and shaped interactive surfaces in the car, related work in other domains is examined where those properties have been applied in interaction design, such as the application of large displays in office environments, or the use of physical affordances for tangible user interfaces. This serves as a basis for the concepts investigated in the following chapters.

Essence The analysis of touch interaction has revealed two main phases - search and selection. Both require glances towards the screen and distract the driver's visual attention off the road scene. Two characteristics of upcoming interactive surfaces in the car cockpit are *largeness* and *shape*. This thesis will focus on the effect of those physical manifestations for the direct interaction with digital interfaces.

Figure 3.10: Trend of growing screen sizes: in different domains like mobile phones, TV sets[35] and for infotainment purposes in cars, screens have grown in the last decades[36].

3.3 Largeness – Increasing interaction space

Due to technological developments, screen spaces have grown in desktop environments. This trend has now reached many other domains, such as smartphones, TV sets and the car interior (see Figure 3.10). The increased area can be used to present information less dense, in more depth, or to display different information at the same time.

Figure 3.11 gives examples of how large, display-only or directly interactive screens, are employed. They are used in office environments to increase the desktop size [24] or to create a medium for group meetings [66], as public information displays [292] or for visualizations in emergency centers [289]. In the horizontal plane, *LambdaTable* [159] is an example for a tiled display, while *metaDESK* [286] shows how an interactive tabletop can be enhanced by tangible objects to browse digital data .

Potential of grown interaction space

Large screen spaces can raise productivity and user satisfaction. Czerwinski et al. [52] showed that for a cognitively loaded task in a desktop environment, where several switches between windows were required, a large display (46") outperformed a small display (15") regarding task completion time, subjective satisfaction and preference. This was caused by easier window management and menu interaction activities due to the larger display size. However, it is crucial to design applications according to the grown space, e.g. in a desktop environment, to make sure users know where their current focus is, or how task bar and monitor space relate to each other. Based on those results, Robertson et al. [234] found that many of those problems (e.g. accessing windows and icons at a distance, task management) can be solved by appropriate graphical user interfaces. Similarly, Anderson et al. [6] conducted a study where users performed tasks that required to switch between different windows, with either a single- or multi-monitor setup. They found an increase in usability regarding ease of learning and time to productivity as well as different performance measures such as task time, completed edits, and errors. They claim two reasons

[35] FlowingData: Television Size Over the Years. `http://flowingdata.com/2009/09/23/tv-size-over-the-past-8-years/` [cited 2013/12/01].

[36] © Photos by BMW Group, Sony, Nokia, Samsung, Tesla.

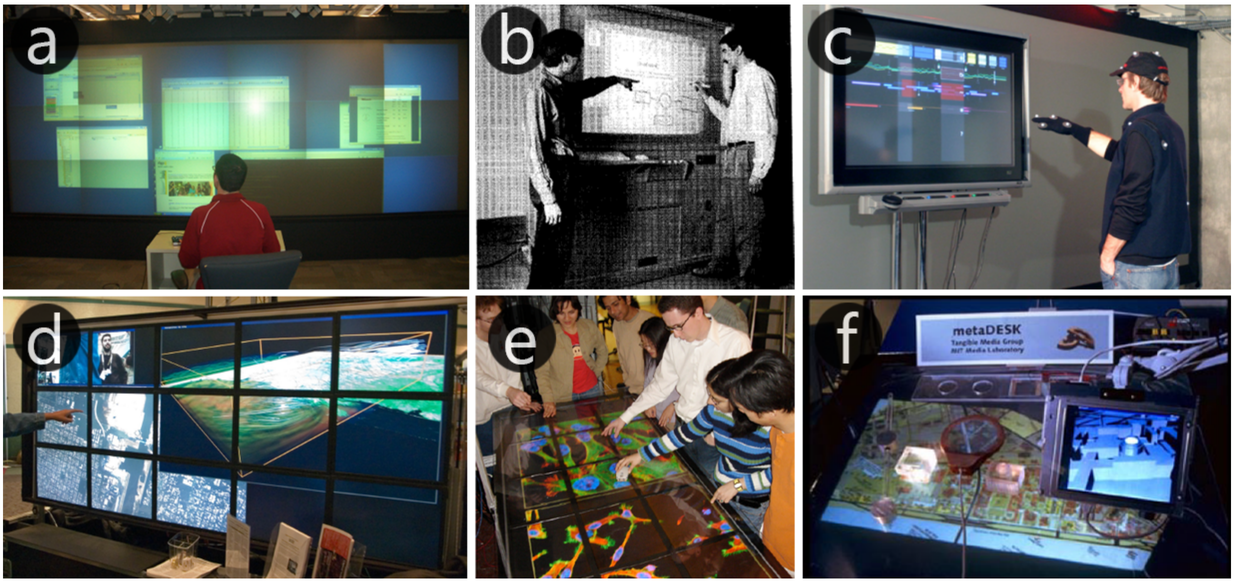

Figure 3.11: Fields of use for large display spaces. Vertical use as a: desktop display [24] b: discussion board (*Liveboard*) [66] c: public information display [292] or for d: visualization of multidimensional data [289]. Horizontal use to e: support group work (*Lamda-Table*) [159] f: display visualizations browsed with tangible objects (*metaDESK*) [286].

that account for the gain in efficiency: larger screen spaces provide improved access to different information at a time simultaneously, but they also ease cognitive processing. When different types or entities of information have a determined position, they can be located more easily. This can be supported by bezels or other structuring elements so people can organize different tasks or information entities better [13]. Bi and Balakrishnan [24] observed display usage in large and multi-monitor environments, and found that people tended to utilize the center of the screen area for their main tasks. Other secondary windows were located in the outer areas of the screen space; this seemed to enhance the awareness for peripheral information. Moreover, for rich information tasks, people preferred frequent window moving to conventional re-sizing behavior.

Challenges of increased display space

The dimensions of large interaction spaces can pose problems for usability, for example regarding window management or tracking of elements such as the cursor [234]. Especially when not the full visual attention is on the screen, it can be difficult to spot a specific detail or change, and maintain an overview. Goldberg et al. [87] evaluated user expectations regarding large displays. They found that (window) objects should always expand to make use of all available space to avoid white spaces, and that everything should always be visible. The task bar should remain stationary so it can be located reliably.

Focusing on both technical and usability issues, Ni and Schmidt [194] provide an overview and highlight several effects of large displays on interface design and interaction, such as the challenges to organize space and to interact with distant areas:

1. Truly seamless tiled displays.
2. Stereoscopic large high-resolution displays.
3. Easily reconfigurable large high-resolution displays.
4. High-performance cluster rendering.
5. Scalability.
6. Design and evaluate large high-resolution display groupware.
7. Effective interaction techniques.
8. Perceptually valid ways of presenting information on the large displays.
9. Empirical evidence for the benefits of large high-resolution displays.
10. Integrating large high-resolution displays into a seamless computing environment.

For the following overview of related work, the focus will be on point 7, i.e. concepts to effectively interact with large display spaces.

3.3.1 Interacting on spacious surfaces

Potential Large displays allow to distribute content spaciously. According to Fitts' law [71], targets can be hit more easily if they are larger, which is true for pointer and for touch input [252]. In addition, studies on mobile phones have shown that increased screen size can raise the efficiency of an information seeking task [221].

Challenge If there is a lot of display space available, we still need to locate content and functionality, so we need to know where to look and click. To direct visual attention, light spot metaphors have been used for wall-sized displays [149], and also for large automotive CIDs; if areas are brightened to guide the user's glance to important information such as warnings, response time can be decreased which in turn leads to an improved driving performance [215]. Similarly, frames and trails around or towards a target item can help for orientation and to reduce task time [113], and, as a result, time of visual distraction. However, all those approaches require visual search.

To support orientation on large displays, there are different approaches to reduce the visual distraction, apart from using non-visual feedback as presented in Section 2.1.3.

Making use of kinesthetic perception

Proprioception allows to sense the position and orientation of the body's parts with respect to each other. Kinesthetic perception is a further sub-category that provides a user with information on muscular contraction leading to a certain positioning [172]. Based on this knowledge, people have been shown to successfully identify different areas in the space around their body [17]. This

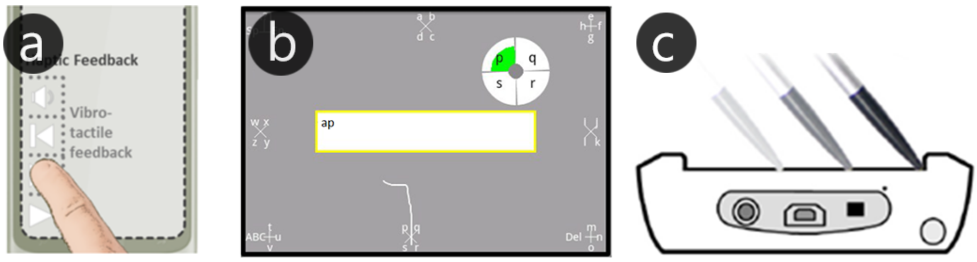

Figure 3.12: Bezels offering orientation on touchscreens. a: Aligning buttons along the screen's bezel [207], b: Combining bezels for entry and further directional movement for text entry [131], c: Using the bezel as a barrier for stylus input [78].

could also help to identify areas on a large screen. Wang et al. [299] showed that absolutely positioned targets on a mobile phone could be hit blindly even in an equal 4x4 layout with an accuracy of more than 80%. Hausen et al.'s *Unadorned Desk* [100] also makes use of the awareness of objects' spatial position. Digital objects such as application shortcuts are virtually placed on the desk next to the keyboard without a visual representation. A user study showed that users are able to retrieve the placed items even without any visual feedback on the screen. People tended to organize items in a grid. Performance was worse for items placed further away and for items placed in the middle of the desk, where the desk outline did not serve as a reference frame; still, the retrieval of up to 10 items was possible without an increasing number of errors.

Offering physical spatial reference

Discussing TUIs, Ishii mentions the fact that "people have developed sophisticated skills for sensing (...) their physical environments" [127]. To ease the orientation in a large uniform surface, already available or artificially added physical objects have been used to support interaction on interactive surfaces (see Figure 3.12). Pielot et al. [207] used bezels of a smartphone screen in a mobile application. By putting buttons along one side of the screen where its border can be haptically perceived, interaction is supported by the tactile feedback and thereby eases the mobile usage, resulting in reduced interaction time and errors as well as increased perceived usability. Jain and Balakrishnan [131] even enabled eyes-free text entry on a smartphone. By providing eight different entry points along the screen's border in combination with different subsequent directional movements, the expressiveness allowed for complex text input. Combining bezels with stylus-input, Froehlich et al. [78] could show that motor-impaired users benefit from the haptic support which compensated for a limited fine motor control. By using a tactile overlay, El-Glaly and Quek introduced physical elements on a touchscreen-based e-reader. Spatial referencing was supported, resulting in an improved access of long texts for visually impaired users, as it helped locating specific areas on the screen [65].

Enabling position-independent control

To avoid the need to locate a menu, Robertson et al. [234] developed *Start Anywhere*, a start menu that opens at the position the cursor is currently located when a designated key is pressed. Similarly, a menu can open anywhere on a touchscreen as soon as a finger is positioned [62].

Eyes-free usage can be supported further when not discrete touches are required but less accurate touch gestures in a certain direction control the interface. To support the learning phase, this can be supported by visual cues [63]; once those directions are learned, menu interaction can take place blindly. We[37] have shown that there are various parameters already available on current touchscreens that can enhance blind touch interaction [240]. Different numbers of touch points at a time as well as multiple successively issued touch points do not require exact positioning. Those commands can be issued blindly and allow the user to concentrate the visual attention on a primary tasks that needs to be observed continuously. These approaches have been combined for example by Bach et al. [10]; one-dimensional touch gestures are combined with single and double taps.

3.3.2 Interacting with distant surfaces

Potential Enlarging an interactive surface with displays of increased size, or taking additional objects in the surrounding into account, the overall interaction space can substantially grow. Objects can be positioned to be peripherally perceivable [101], and the main interactive area can be kept clear and uncluttered [100].

Challenge Greatly enlarged interactive surfaces can get out of direct reach for the user. Direct touch interaction is then not suitable for controlling the display, so there is a need to find new ways of interaction.

Bringing distant objects closer to the user

There are different approaches that allow to access objects which are not in the user's direct reach. Their drawback is that they require an extra step before the actual interaction can take place, and they partially rely on remote instead of direct control.

In multi-monitor environments, people tend to assign the center of their screen space as their main working area [24], and use drag & drop techniques to move required windows there to work with them. There are different approaches to support this activity. Robertson et al. [234] proposed different interface prototypes to ease the selection of distant windows, by enabling small hand movements to select from a wide range of objects, or by dragging whole portions of the screen to the center of the screen temporarily like when dragging a tablecloth to access a salt shaker. Similar to that, Khan et al. [148] proposed *Frisbee*, a technique that allowed the user to create a local representation of remote target areas, where changes in one visualization affect both instances. The overall spatial proportions stay the same, unlike in distorting visualizations such as fish-eyes views, so the spatial sense of the user is preserved. Baudisch et al. [19] introduced two techniques called drag-and-pop and drag-and-pick that take into account the user intention when supporting the selection of distant objects. When the user initiates a dragging action, the system identifies potential target objects and creates representations that pop up close to the cursor's position, to shorten the way for the user.

[37] The results have been published in: S. Rümelin, V. Kroner, and A. Butz. Simple Nonvisual Intraction on Touch Tablets. In *Proceedings of Mensch und Computer 2013*, pages 241-250, Munich, Germany, 2013. Oldenbourg Verlag [243]. The prototype was implemented by Valerie Kroner in the course of her diploma thesis [156], under the supervision of Sonja Rümelin and Carsten Thomas.

Using deictic gestures to interact with distant areas

Gestures are an "expressive form of human communication" [298]. Gestures can be intended or unintended. If issued with intent, they can either be manipulative and act on something in the environment, or be communicative. The latter can further be divided in acting and symbolic gestures. Acts can either be mimetic when imitating an action, or *deictic* when pointing [206].

Applications Using gestures to control a presentation application, Baudel et al. [16] emphasize the potential of deictic gestures as a natural means for defining a location. Moreover, they highlight the short as well as substantial interaction and the ability of direct interaction with objects. Bolt [27] applied pointing for the selection of objects and for the definition of target positions on a distant screen. Speech commands such as "Put that there" are used to further specify the interaction. Gestures have been widely applied in robotics [203, 116]; Richarz et al. [227] instructed robots to walk towards the pointed direction with an additional "There you go". Pointing towards a certain direction, vibrotactile feedback has been used to inform the user about a destination's direction in a navigation scenario [235]. In AR applications, pointing can be combined with a visual display when pointing with a smartphone (e.g. Wikitude[38]). The camera image of the respective direction is augmented with additional virtual information, based on orientation and location data.

To visualize pointing, Shoemaker et al. [267] proposed to use real or virtual shadows on the screen, which the user's body would throw on the wall when the light source was located behind them. In that way, the user's movements are embodied on the screen and make the interaction easy to understand. With the advent of 3D HUDs in the car, it might even become possible to highlight selected points of interest (POIs) directly in a street scene through AR visualizations [80].

Recognition Pointing can be sensed by either optical systems or sensing devices attached to the user [189] such as data gloves [16]. The latter requires that the user is equipped with some device, so optical systems are often preferred.

Nickel and Stiefelhagen identified three phases when pointing [195]. First, the hand moves towards the target. It remains still in this pointing position and finally, it moves away from it. To determine the pointing direction, either the orientation of the user's hand or the vector from the user's head through his hand can be used [188]. The intersection of this vector with the environment describes the selected object. Nickel and Stiefelhagen [195] compared using either the head-hand-vector to forearm or head orientation. In most cases, the direction described by head and hand delivered the best results. However, the most appropriate vector might also depend on the actual posture of the arm, which can be either bent or stretched out for targets further away [60]. Wong and Gutwin [315] investigated pointing accuracy on targets located in a distance of 3 and 6 meters in a camera-based setting. Gestures were translated into VR and interpreted with a mean angular error of less than 5°, with errors significantly smaller when the distance was larger. Overall, pointing recognition already seems to be sufficient for a wide range of applications.

[38] `http:\www.wikitude.com` [cited 2013/12/13]

3.3.3 Interacting jointly on large surfaces

Potential Large surfaces allow that several people can work together in the same interaction space. Tuddenham and Davies [284] developed *Websurface*, a shared tabletop where people are sitting on one edge of the table while cooperating. They state that in comparison with a dual laptop setup, the common large space helps to share working items, by allowing to pass the items in a lightweight, non-disruptive way and to better observe the activities of the other. Looking for desired locations for in-car touchscreens, the center console has been stated to be favorable because it enables large screens on which information can be shared with the front-seat passenger [103].

Challenge Sharing an interaction space involves the danger of conflicts; if two people reach for the same object, collisions might occur or interaction might be unequally distributed.

Territoriality in tabletop interaction

When people are collaborating on traditional tabletops, Scott et al. found that they create different territories to organize the shared work [262]. *Personal territories* are used by a single person, for example to prepare a group contribution. They are located close to their owners, often directly in front of them. For shared activities, *group territories* are used, often in the center of the overall working area. Here, collaborators support each other and exchange resources, to accomplish the main task. *Storage territories* complete the setup. Task-related items that are currently not in use or only serve as auxiliary objects, but also non-task items such as food or drinks, are placed here. They are loosely organized and can be moved across the table or merged with other territories. Inside the territories, items may be placed scattered when searching for an item, or piled to declutter the workplace.

Doucette et al. [59] followed up and investigated the usage of a digital tabletop where two people interacted on the whole table sitting next to each other on one side of the table. They confirmed territoriality behavior on digital tables and highlighted that the relationship of people has an effect on territorial behavior; when the relationship is more intimate, people tend to invade the other's personal territory more likely. Tuddenham and Davies [284] emphasized the benefit of territories for organizing individual and group work when working side by side on a digital tabletop. When working with two remote controls on one display, people tend to divide the screen in a left and right working area, assigning the partitions according to their seating position [283].

Orientation can become a problem when people sit facing each other, so that text is only legible for one of them. However, reorienting texts can also be used to manage group work: the orientation makes clear who is working with a certain item [158], and a rotation towards a collaborator indicates a change of ownership [158]. Moreover, privacy is supported as others can not easily see what is drawn [280].

Critical factors for seamless interaction

Different aspects need to be guaranteed to allow for seamless interaction.

Enable awareness Hornecker et al. [118] pointed out the importance of awareness in collaborative environments. Seeing the other's physical actions and their results helps to maintain an overall overview, which works better on touch surfaces than with remote controls. Positive indicators for awareness are unsolicited assistance and non-verbalized handovers. For remote collaboration settings, territoriality behavior is less distinctive, and awareness is harder to achieve; virtual shadow arms have been used to pronounce the other's activities [285].

Avoid collisions Collisions occur when several people reach for the same item. People tend to avoid collisions implicitly; direct touch interaction is preferred to indirect input, as people are more aware of the others' movements and selections [59]. Especially on large interactive surfaces, people tend to feel uncomfortable when reaching for very distant areas; the tendency to create personal spaces in direct proximity to one's position, thus distant from the collaborators, serves as a natural barrier to intrusions of the others. Replicated controls are preferred to shared controls; they can be placed in comfortable reach and there is less interference when the access does not have to be alternated [190].

Avoid domination Especially when parties have different abilities and capacities, single persons can tend to dominate the interactions and block other attendees. This can be unintentional and be solved by raising everyone's mutual awareness. Otherwise, conflict management tools can help to solve issues with unequal cooperation. Alternating access to control can be implemented in the system by assigning specific actions to dedicated positions around a table [209]. Moreover, piece ownership can guarantee that actions related to the respective piece are performed by the owner and therefore, all parties contribute to a group task. Otherwise, a shared tangible objects can be used to hand over and visualize a change in control, and enable access to functionality and content [199].

Enable negotiation More important than forcing alternate access and prevent interference might be to provide tools to negotiate critical situations [118]. Offering undo functionality can help to control the other's actions, and to correct actions jointly. This is especially useful for learning environments, as it allows to demonstrate cause-effect relationships [74]. However, it might also promote blocking strategies where one user tries to prevent the other from doing something, and might be misused by a dominating user.

Essence

Display spaces have grown in size in many application areas. They provide the potential to raise productivity by allowing parallel access to different information at a time. They also raise challenges with regard to orientation and effective interaction; however, there are different approaches to maintain an overview of spacious surfaces even non-visually. As interactive spaces have grown substantially, touch interaction will become impossible. Inspired by robotics, deictic gestures can provide a new way for direct interaction. If multiple persons work in the same interactive space concurrently, they tend to create territories. Potential conflicts such as collisions or domination in the different territories have been shown to be solvable by appropriate interface concepts.

3.4 Shape – Adding a further dimension to interaction

Currently available displays, big or small, with or without touch sensitivity, are planar. Due to technological advances (see Section 2.2), it will be possible to have non-flat, such as curved, waved or otherwise shaped surfaces for future displays. They will feature new properties that can be used to enhance human-machine interaction.

Models of non-planarity

There have been different models that describe the design space of shape-changing and shaped surfaces. They can be used to find similarities and differences of existing research and inspire new designs in vacant areas.

Parkes and Ishii [204] have classified shape-changing devices according to their motion-prototyping aspect. Focusing on the process of motion, mechanical (rotational, linear, radial), material (rigid, layered, skeletal, amorphous) and behavioral (speed, direction, acceleration, twitter, delay, pattern) properties are defined. Rasmussen et al. [222] named different categories of shape change but with a focus on what the object itself looks like, leading further towards a space of possible shapes. They found eight types of shape change, distinguishing between topologically equivalent (orientation, form, volume, texture, viscosity, spatiality) and not topologically equivalent (adding/subtracting, permeability). Among those, the parameters *orientation*, *form*, *volume*, and *texture* can be used to characterize the final surface shape. A metric for shape resolution has been proposed by Roudaut et al. [237]. They defined ten features, and explored different technologies to vary those features. Some of them are related to the final state of the object after a shape change, among them *area*, *granularity* (in the sense of how detailed the shape is), and different properties defining further details of the shape (*curvature*, *amplitude*, *closure*, and *zero-crossing*).

More specifically for static surface shapes, we[39] have presented a first attempt towards classifying the design space for non-flat interactive displays, focusing on architecture and interaction features [239]. On the one hand, architectural properties such as *shape*, *size*, *curvature* and *structure* describe how non-flat objects are built, which is related to the properties of final states in the models described before. On the other hand, interaction-related properties describe how users interact with the interactive surfaces, by defining which *modality* is used or what influence the *texture* has on different aspects of perception. Figure 3.13 shows a parallel coordinate plot summarizing this approach. Two examples of shaped interactive surfaces are drawn in: the interactive advertising column of Beyer et al. [23] and Wimmer et al.'s *Curve* [312], a large display combining vertical and horizontal working areas.

Identifying texture as a dimension of non-flat surfaces and reviewing research of shaped interactive surfaces, we found that it is still an open question how surface texture influences the interaction, explicitly and implicitly.

[39] The design space has been published in: S. Rümelin, G. Beyer, F. Hennecke, A. Tabard, and A. Butz. Towards a Design Space for Non-Flat Interactive Displays. In *Workshop 'Beyond Flat Displays: Towards Shaped and Deformable Interactive Surfaces' in conjunction with the ACM SIGCHI Interactive Tabletops and Surfaces 2012 Conference (ITS '12)*, 2012. [239].

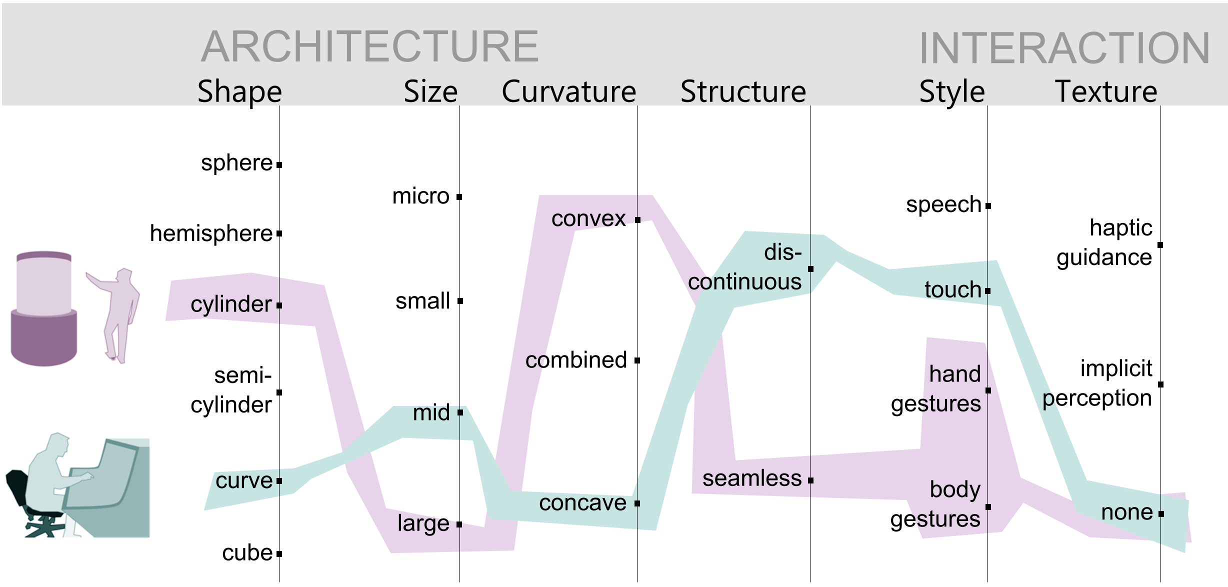

Figure 3.13: Design space for static non-flat interactive surfaces. Architectural properties such as shape, size, curvature and structure describe how non-flat objects are built, while interaction-related properties define the interaction [239].

Potential of non-planarity

Displays offer the possibility to interact with graphical representations of data, and with the advent of touch sensing technology, the user can manipulate them directly with the finger tips. Some specific multitouch gestures, such as pinching or zooming, have become de-facto standards, and a common interaction vocabulary is starting to form. What touchscreens lack, however, is expressive feedback; with hardware keyboards, people have been able to perform text entry blindly, relying only on the feedback the hardware buttons provide [272]. Tactile and acoustic feedback, or advanced interaction concepts as presented in Section 3.3.1 try to solve the issue that flat surfaces themselves do not provide haptic feedback. If we can now design non-planar interactive surfaces, it will again become possible to offer the user something to grasp for, to provide orientation on the surface. In 2004, Holman and Vertegaal [115] have defined the term *organic user interface (OUI)*. They claimed the idea of interactive objects featuring organic shapes, with the ability to display content rather than serving as a pure input device like *tangible user interfaces (TUIs)* did at that time. They highlight the goal to have interactive devices integrate into non-planar objects. Therefore, when the form factor of interactive surfaces is no longer restricted to a flat rectangle, the integration in existing shapes becomes possible.

Challenges of new display shapes

The field of shaped interactive surfaces is relatively new. It will be required to see how people react to surfaces they do neither expect to be a display nor to be interactive. We need to have people interact with those surfaces and see what affordances they offer. Regarding the aspect of

Figure 3.14: Enhancing displayed content by surface shape. a: 3D data on the three-dimensionally shaped *Sphere* [22] b: *StarFire* [282] c: *Curve* with perspective+detail [258].

blind interaction, a challenge will be to evaluate different parameters of shape and investigate which features are easy and clear to perceive, and what kind of functionality can be supported.

3.4.1 Enhancing displayed content

Three-dimensionally shaped interactive surfaces allow to present 3D data on a 3D shape. This is especially useful when the data fits the shape, as in the case of presenting a globe on the spherical display *Sphere* [22] (Figure 3.14a). When 2D data is displayed, it is critical that content is supported by the shape, as otherwise the ability to interpret the information might be degraded compared to a flat display. Stevenson et al. [275] presented different use cases for an either convex or concave shaped display, not by dynamically changing the orientation but by presenting applications for the different states to highlight the versatility of a deformable display. A circular convex bending can support a zoomed 2D map view similar to a fisheye visualization, while in a concave state the display might look like a steel pan drum and can be used as a musical instrument. Interaction should then make use of physical affordances provided by the shape [273]. On the technical side, distortions need to be corrected, for example by pre-distorting content for a respective shape [238].

Different concepts for workplace environments such as *StarFire concept* [282], *Curve* [312] and *BendDesk* [306] have presented large and curved displays that integrate both vertical and horizontal portions (see Figure 3.14b). Such smoothly shaped displays allow for seamless visualizations across differently orientated display portions. Moreover, it is beneficial that it puts the whole screen space in direct touch distance [268].

Völker et al. [294] showed that flicking on the curved surface of the *BendDesk* is influenced by the non-flat screen portion in-between, and they emphasize the need to understand how people interact on shaped surfaces. Some known principles still hold true for curved displays, such as Fitts' law for pointing across different display orientation [107]; there has even been a positive effect on dragging accuracy from one part to the other using touch input, compared to a connection through a sharp edge [108]. Moreover, Schwarz et al. [258] have extended a virtual two-dimensional overview display on the *Curve* with a HUD visualization providing a second viewing perspective. Integrating the vertical curve, perspective and detail views can be seamlessly merged (see Figure 3.14c). Shape can further be used to initiate interaction when information is displayed on a portion of the screen that is not fully visible from a certain perspective or as an animation all around, as it requires the user to move [23]. This property can also be beneficial for privacy reasons; only people nearby are able to see the same content [28].

3.4.2 Enhancing interaction

By making use of the sense of touch, shaped surfaces can not only enhance the visual presentation, but also enrich the interaction with objects in terms of affordances and feedback.

Surface haptics and control element haptics For the different stages of the interaction with touchscreens, namely the search and the selection task (see Section 3.1), haptics can support the user in different ways.

Tactile sensations gathered through the cutaneous sense indicate surface features and let the user feel textures of the user interface such as edges; the cutaneous sense works as a spatio-temporal filter [172]. *Surface haptics* define those characteristics [295]. Instead of sensing real geometric features of the surface, touch force sensing [270] and electrostatics [15] have been applied to create virtual textures. Surface haptics play an important role in quality perception for example in the textile and paper industry [224]. In the automotive domain, surface haptics support the user in identifying control elements in the search task. The German terms "Such-" [48] or "Oberflächenhaptik" [218] can be used to describe features of the surface that help to identify specific elements. MacLean refers to this phenomenon as "haptic glances" [176].
On traditional touchscreens, the tactile sensation does not differ for the contact with and the selection of a virtual button. *Control element haptics* of physical push buttons separate the two steps. Following the initial contact with the element, the user needs to overcome a certain resistance when pressing; this progression can be characterized by a force curve. The button's mechanical limit stop then indicates when the button is finally actuated [225]. The German terms "Bedien-" [271] or "Betätigungshaptik" [225] are used to describe those two characteristics that define the haptic feedback confirming an interaction.

Categories of perception Loomis and Lederman [172] define different categories of perception based on the sense of touch and the sense of motion.

Tactile perception occurs in the context of a static posture, and is driven by the cutaneous sense. Examples are Braille reading, or patterns drawn onto the back, where the part of the body that perceives the stimulus is not moving at the time of perception [172].
In contrast, *kinesthetic perception* (see Section 3.3.1) refers to the sense of movement. Variations in the orientation of limbs provide information on the movement of the muscoloskeletal system; this can be triggered by an active pointing gesture or by a passive movement excited by a force-feedback system [172].
Haptic perception describes the interplay between tactile and kinesthetic perception. Both contribute to the overall perception, for example when actively sensing for haptic cues on the surface of an object. The exploratory movement refers to the kinesthetic part while the perception for example on the fingertip refers to tactile perception [172]. MacLean [175] highlights the potential

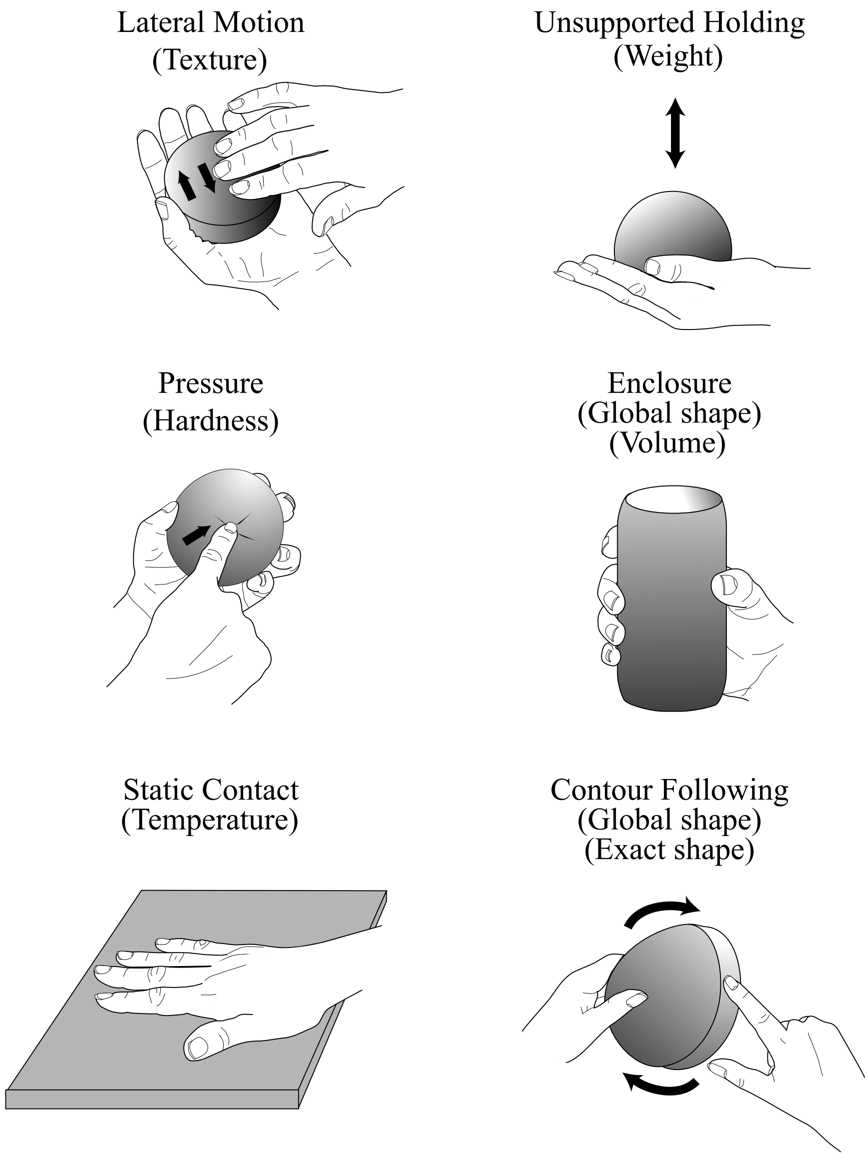

Figure 3.15: Typical movement patterns for exploratory procedures resulting in haptic perception[40]. Details are in the text.

of integrating different haptic modalities for rich feedback, calling it multihaptics. Static contact can be used to perceive the temperature or other material properties, but it might often not be sufficient to just touch an object. In contrast, it can be required to navigate back and forth to scan its properties through the cutaneous sense. Lederman and Klatzky describe different exploratory procedures [162]. They name different patterns, such as *lateral motion* which refers to a scanning behavior over an object's surface, but also *enclosure* or *contour following* (see Figure 3.15).

[40] With kind permission of Roberta L. Klatzky. This figure originally appeared as Figure 1 in [162]. With permission of the authors, the original figure was modified and published by Oxford Press as Figure 5.1 in [135].

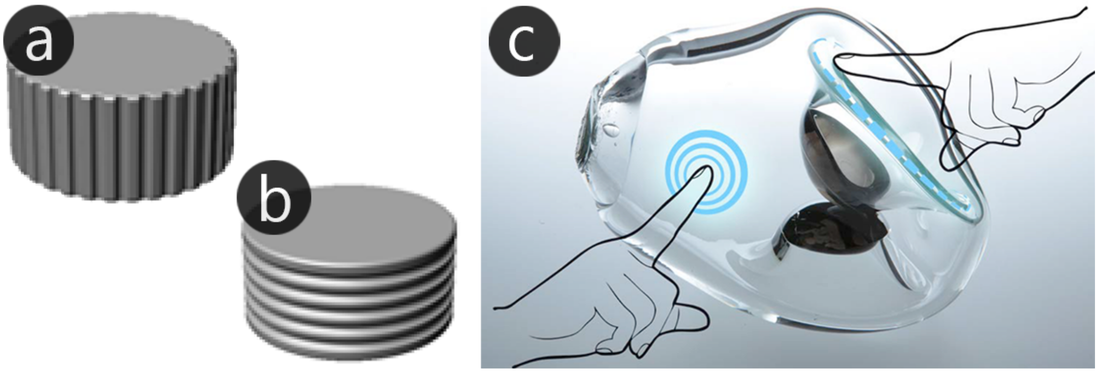

Figure 3.16: Offering affordances through surface shape. Differently oriented riffles afford either a: rotating or b: pushing [90] c: Glass object used to explore affordances of different shapes and surface structures [254].

Affordances provided by shaped surfaces

Definition Affordances are the actions that are possible to be performed within a certain environment with a certain object [86]; perceived affordances [196] have been widely used to describe the design aspects that suggest how to use a physical object. In 2008, Don Norman added the notion of signifiers in an attempt to clarify the difference between the physical actions that are possible (*affordances*), and explicit and implicit clues that communicate them (*signifiers*) [197].

No matter what term is actually used, Ishii stated that not only for the interaction with real objects, but also with digital data it is important to provide the user with physical handles. There is a need for something to "bridge the gaps between both cyberspace and the physical environment, (...) to maximize the legibility of interface [sic!]" [129]. TUIs such as *Toolstone* have from then on been designed to "effectively use the human's physical manipulation skills" [226].

Examples So what does shape communicate to impact and potentially ease the gulf of execution? Cuijpers et al. [49] investigated user behavior when interacting with objects of different geometric properties. They found an influence of both width and orientation on the grasping trajectory as well as the hand orientation when approaching the object. Similarly, the texture of an object (high, medium and low-friction) influences the way objects are approached, and if they are grasped on-the-fly or if the hand is stopped before making the grab gesture [73]. Non-flat surfaces can afford how fingers are placed on a surface. Offering two concave shaped circular edges around a cylindrical object, people changed their grasping behavior compared to a flat surface and positioned their fingers in a way that they were supported by the edges [251].

Regarding texture on haptic control elements, Götz [90] showed that the orientation of lines on a ribbed surfaces has an influence on how users think an element has to be controlled; movements perpendicular to the riffles are preferred. Therefore, a rotational movement is afforded when the lines are perpendicular to the rotational direction (Figure 3.16a) as they offer grip for the rotating movement, which has also been used to support interaction in the TUI domain [39]. A different orientation (Figure 3.16b) indicates to push it. This also applies for textures on non-movable

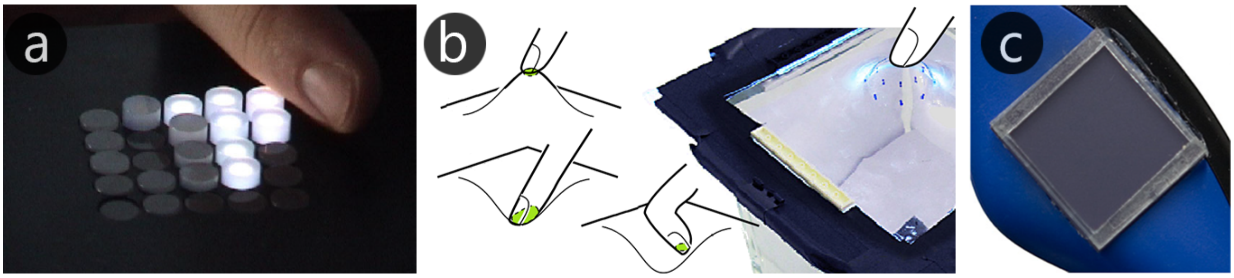

Figure 3.17: Surface shapes providing haptic feedback. a: Dynamically changing haptic properties in *Lumen* [219] b: Convex and concave bulges [238] c: Attaching overlays to create haptic guidance [88]

elements; in a project on affordances of static objects made of glass, we[41] explored the design space of materiality and shapes [254]. There, we found that edges and elongated indentations afford to be used as a finger guide when performing an interaction along the structure. Moreover, hollow-like indentations afford to put a finger into it and can help to secure a finger at a specific location while further interacting with other fingers outside the shape.

Feedback provided by shaped surfaces

Appropriate feedback can help to overcome the gulf of evaluation, thus support and confirm a user's interaction with an interactive system. Tactile [114] and kinesthetic [229] feedback has been shown to support interaction with touchscreens in mobile situations. Introducing shaped surfaces can extend those approaches to make use of haptic perception and provide rich multi-haptics feedback.

Dynamic and static haptic feedback Haptic feedback can be either generated dynamically or be there statically.

Vibrations or actuated surfaces are examples for *dynamic haptics*. They mechanically generate feedback during an interaction. Vibrations can be used to provide tactile sensations for a surface as a whole [81]. Using an array of electromagnets in combination with an overlay containing magnetorheological fluid, Jansen et al. [132] developed *MudPad*, a device that allows for localized tactile feedback. This is especially interesting for multitouch capable touch surfaces where each touch should be assigned with an individual feedback sensation. Similar, electrostatic feedback as in *TeslaTouch* [15] creates subtle localized feedback on the fingertip by controlling the electrostatic friction between the touch surface and the finger. By transferring the tactile feedback to a remote location like the user's back or the second hand, it becomes possible to provide feedback even when there is no direct contact with the interactive surface [230]. *HapTouch* [229] is a force-sensitive screen that is movable in z-direction (away or towards the user) and additionally uses tactile feedback adjusted to different pressure forces. Similarly, *TouchMover* [270] uses

[41] The results have been published in: M. Schmid, S. Rümelin, and H. Richter. Empowering Materiality: Inspiring the Design of Tangible Interactions. In *Proceedings of the International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*, pages 91-98, New York, NY, USA, 2013. ACM Press [254]. The prototypes have been implemented by the participants of the "Designworkshop" in the summer semester 2012, under the supervision of Magdalena Schmid and Hendrik Richter.
`http://www.medien.ifi.lmu.de/lehre/ss12/bmwdw/` [cited 2013-12-16]

force sensing and 1D haptic actuation to enhance touchscreens with haptic feedback. Interactive elements are activated not just by touching the screen surface, but by physically moving the screen by a certain amount (i.e. with a certain activation force), like it is done with traditional hardware buttons. Alternatively, single portions of a screen can be actuated and displaced to communicate a certain action. This has been shown in low resolution in *Lumen* [219] (see Figure 3.17a).

Overall, the approaches for dynamic haptic feedback can enrich the interaction but are only to some extent suitable for the setting in a car where driving vibrations could interfere. In contrast to dynamically generated feedback, *static haptics* describe features of the surface that are persistent and do not change during the interaction. Roudaut et al. [238] investigated the ergonomic effects on touch interaction for spherically formed structures of different size and orientation with deformed acrylic glass (see Figure 3.17b). Harrison investigated similar shapes but created them with "inflatable buttons", built upon a rear projected display [95]. The acrylic front layer includes cut-out parts and is covered with a latex layer; the space behind it is hermetically sealed and can be either positively or negatively pressurized to create either concave or convex features on the surface. Other methods of manufacturing are to attach material such as acrylic cut-outs [277] or label material [65] onto an existing surface. New technologies promise the lightweight realization of flexible but static surfaces: for example, Tactus Technology[42] has shown an approach to raise haptic elements such as keyboard buttons from a flat surface by introducing an additional top layer that can be filled with fluids on demand to create the keys [278].

Examples Different surface structures can support haptic perception in different ways. Evaluating differently oriented round bulges in a flat surrounding surface, Harrison showed that concave shapes provided haptic guidance towards a final finger position and afforded to "stay in there" by offering a hold [95]. In contrast, outward facing orientation gave more pointed feedback on the tip of the shape, making it easier to hit a trigger point exactly. Such convex features do not require to slide in, but allow simple tapping known from common physical buttons [95].

Raised edges around a flat interactive surface have been used to support text entry with a stylus by providing stability when using an edge-based alphabet [314], when compared to unsupported strokes. This principle has been transferred to touch text input in the car, by placing a touchpad with a haptic rectangular border onto the steering wheel (see Figure 3.17c). Gonzales et al. [88] showed that text input performed with the thumb on it allowed for a faster task completion time compared to list selection and other text input methods, while driving speed was still reasonable. In a list selection task, Swette et al. [277] also added static haptic structures to a touchpad in an automotive center console; circular and rectangular edges allowed participants to quickly find the interaction space where lists could be accessed and they supported circular or linear scrolling gestures.

Regarding the resolution of perception, Freyberger [77] conducted experiments to investigate which geometric properties of an object's edge can be haptically distinguished. Participants had to identify different angles in pairwise comparisons. While for larger angles of more than 90°, resolutions of 7° were distinguishable, recognition for sharp edges showed to be less fine-grained. Only differences of about 20° could be resolved. This demonstrates the haptic perception is able to discriminate small differences, but that it also strongly depends on the context.

[42] `http://www.tactustechnology.com/technology.html` [cited 2013-12-17]

Essence First approaches to define the design space for shaped surfaces indicate that there is a wide range of possible forms that future interactive objects can take. On the one hand, this can be used to emphasize visualizations. On the other hand, surface shape can communicate possible actions and strengthen the feedback of direct interaction. Haptic perception, which integrates both tactile and kinesthetic perception, is a rich perceptual channel that can perceive coarse and fine-grained surface shapes.

3.5 Conclusion

Automotive interfaces have started and will potentially continue to integrate interactive surfaces. Direct interaction provides advantages regarding understandability. However, in the car where visual attention towards the human-machine interface for non-primary interaction has to be as low as possible, new ways of interaction need to be explored to cope with the lack of haptic feedback. Two physical characteristics, *largeness* and *shape*, have been investigated in other fields of research and have shown potential to support the interaction (see Table 3.2).

LARGENESS	SHAPE
Increased overview [24] and efficiency [221] through spacious distribution	Inherent provision of signifiers and affordances [251]
Improved targeting through increased size of interactive elements [71]	Tailor-made support through different shapes [238]
Expressive interaction by taking surrounding objects into account [316]	Increased realism of the interface through multihaptics interaction [169]
Cooperative task completion through increased interaction space [284]	Improved perceived quality through expressive feedback [211] and rich contact [38]
Peripheral perception of information [101]	Reduced errors, task time [165] and visual attention [95]

Table 3.2: Potential of size and shape of interactive surfaces.

In the next step, Chapter 4 and 5 will discuss concepts that make use of those properties of interactive surfaces in the car, and evaluate how those can influence aspects such as usability, driving behavior and distraction.

Chapter 4

Large Interactive Surfaces

Concept cars such as Toyota's Fun Vii or Daimler's DICE have presented the integration of large screens into the car (see Section 3.1.2), forming a large interactive surface spanning over the whole cockpit. Additionally, even interaction with objects that are not interactive themselves can be recognized through advanced sensing technologies (see Section 2.2.2). Therefore, we are in the process of enhancing our whole environment with interactive surfaces, composed by touch-sensitive displays, sensing devices and the objects around us.

This chapter discusses approaches to realize the interaction with such large interactive surfaces. Visual attention is required for a direct interaction with interactive surfaces, to identify virtual and real objects. Depending on the passenger situation, different approaches are taken into account, to provide solutions how to support eyes-free interaction in the context of large interactive spaces.

4.1 Passenger situations and cockpit configurations

Meschtscherjakov et al. [186] have defined different interaction spaces in the car interior. For the front area, they define a *driver space* on the left and a *front seat passenger space* on the right-hand side of the cockpit[43]. This indicates that when designing interaction in the car, one needs to consider what persons are present and in the car's "crew" [161]; there can either be just the driver, or the driver together with a (front seat) passenger. Moreover, interactive surfaces are normally in direct reach of the person who is interacting, but with the advent of large interactive spaces, the objects to interact with may get out of direct reach. Thus, this chapter will investigate the following situations (see Figure 4.1):

When the driver is on his own, the whole interactive space is used only by him. For the driver space which is in the direct proximity, the problem is how to enable touch interaction with the large and often flat interactive surface. Section 4.2 discusses how to appropriately use such

[43] They also define a rear seat passenger space which is neglected for this analysis as we focus on interaction in the cockpit area.

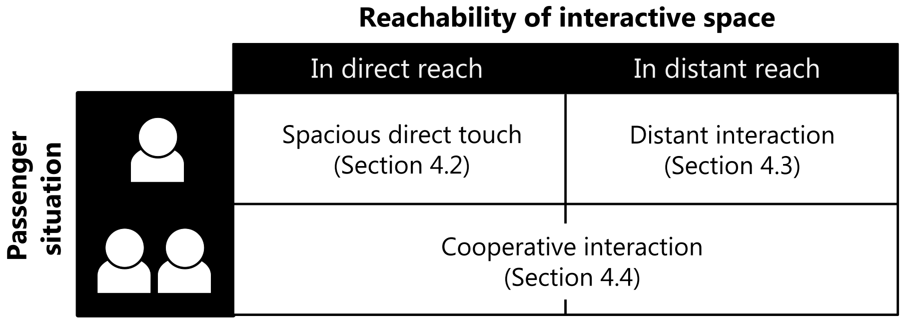

Figure 4.1: Overview of different passenger situations and cockpit configurations.

spacious surfaces. For sections that are out of direct reach, the problem is how to access those distant spaces. Section 4.3 presents an approach to allow for **direct interaction with distant objects**. When a fellow passenger is present, one scenario is that the two individuals use their particular interactive space. For the driver, this does not differ from the situation when no other person is present, while for the passenger, the interaction is not restricted. If they share the space that is available and perform upcoming tasks cooperatively, overall visual and cognitive load can potentially be shared. Section 4.4 discusses how **dedicated spaces** can be used to enable cooperative task completion.

4.2 Spacious interaction spaces

Section 4.2 is based on: S. Rümelin and A. Butz. How To Make Large Touch Screens Usable While Driving. In *Proceedings of the International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '13)*, pages 48-55, New York, NY, USA, 2013. ACM Press [241]. The prototype was implemented by Sonja Rümelin.

Driver distraction has been defined to occur when one does not allocate enough attention to the driving task (see Section 2.1.2); if the driving task does not require a lot of attention, it is available for other tasks. Large displays have the potential to present information generously and concurrently (see Section 3.3.1), to be used in situations when attention is available. This can be an undemanding driving context or a stationary situation. However, unlike physical controls, a display's content and functionality can be adjusted and also present a reduced interface to match a different context. For attention-demanding driving situations, we do not need complex infotainment functionality but quick access to frequently used and most relevant functions. Displays and controls need to be adapted to require as little visual attention as possible, while still enabling to handle basic functionality.

The goal is to find ways how direct touch interaction can be designed for large flat screens to allow for an eyes-free interaction despite their missing tactile feedback. Different approaches introduced in Section 3.3.1 enable direct interaction on large interactive surfaces and their immediate environment without the need to focus the visual attention on the screen. They have been investigated in domains such as mobile computing and partly in the automotive domain. In this section, a comprehensive comparison with state-of-the art in-car controls regarding visual distraction as well as primary and secondary task performance.

4.2.1 *SimplePlayer*: Eyes-free interaction with reduced controls

Approaches to not focus visual attention on the interaction

Different approaches for how to interact with large screens in direct reach have been proposed. First, controls can be enlarged so that they do not have to be targeted accurately; *kinesthetic perception* supports the orientation in the interactive space. Second, *tangible reference points* can support the spatial orientation and enhance or even replace the visual search; haptic guidance can be provided by physical objects such as the screen's border or integrated control elements, and interactive elements can be targeted from there without the need to locate them visually. Third, *position-independent controls* based on touch gestures reduce the need to locate an interactive element on the screen. The user places the hand somewhere on the screen and swipes towards a certain direction from that starting point.

Potential use cases

Commonly used applications while driving are navigation systems, media players and climate controls. While the first only requires initial interaction for the entry of a destination and subsequently is mainly output-only, the other two require continuous interaction to adjust the previously configured playlist or settings. This is done via short, straightforward commands. The adjustments are performed regularly and on short notice as the demand arises suddenly when the user dislikes the current song or feels too warm or cold.

Realization

Music player control has often been used to evaluate automotive user interfaces, for both established physical controls and screen-based systems in the center console [10], but also novel interaction concepts on the steering wheel [58]. Listening to and controlling music is a common secondary task not only while driving. Therefore, it does not require a lot of time that study participants get familiarized with the task, neither in general nor for in-car usage. To evaluate the three different approaches, we chose a music player application with six sub tasks - play, pause, and skip songs and playlists forward and backward. Interfaces were designed for a 17" touch-screen integrated upright in the center console of a car mock-up (see Figure 4.4), similar to the largest currently available touchscreen in Tesla's Model S[44].

To ease the targeting task and make best use of kinesthetic perception, *SpaceTouch* uses maximally enlarged interactive areas (see Figure 4.2). The buttons have a size of 64 x 70 mm (44.8 cm^2). *KnobTouch* is designed around a physical control element attached to the lower

[44] `http://www.teslamotors.com/models` [cited 2014/02/20]

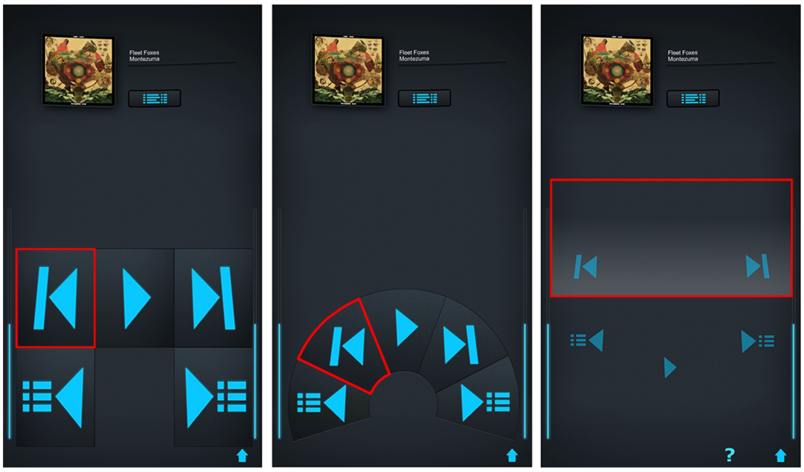

Figure 4.2: *SimplePlayer* interfaces realizing different approaches on a large screen. From left to right: SpaceTouch, KnobTouch, SwipeTouch. As an example, the size of the interactive area for *skip song backward* is highlighted.

part of the screen, which is intended to provide a spatial reference point. Buttons are aligned around it in equal distance as a pie menu [42]. Referring to Ecker et al. [62], the area below the knob from 110° to 250° (clockwise, starting from the top), which is covered by the interacting hand, is left out. The button size (28.7 cm^2) is maximized to fit the screen (overall radius 90 mm, button height 64 mm). Third, the touch gesture interface is called *SwipeTouch*. Gestures should be unambiguous to avoid recognition errors, and should be easy to learn. The most commonly used touch gesture in CE devices is a swipe. A horizontal movement to the left or right is often used to switch between screens in mobile devices. Here, it is used to switch songs and playlists. Referring to Pirhonen et al. [210], a movement from left to right is used for forward. To stay with a one-finger-gesture [155], while enlarging the available gesture set, the screen is split into two large areas. Each has a size of 156.0 cm^2. A horizontal swipe in the top area controls songs, while in the bottom area it controls playlists. A vertical swipe, performed anywhere on the screen, is used for play and pause. In preliminary tests, a downward-moving gesture was found to be quickly performed and thus well-suited to pause playing music. The contrary movement towards the top was intended to trigger the play command, however, it was found to be a) uncomfortable to perform and b) irritating because play and pause are commonly understood as alternating functions and implemented accordingly in the other interfaces. Therefore, we decided that a downward touch gesture is triggering either play or pause, depending on the current music state.

4.2.2 Evaluation – Music player control

We conducted a user study to evaluate the different interface approaches for the interaction with frequent controls on large touchscreens, using kinesthetic perception, tangible reference points and position-independent controls. Additionally, we included a state-of-the-art remote controller interface as well as a touch interface based on standard-sized buttons for the comparison of the

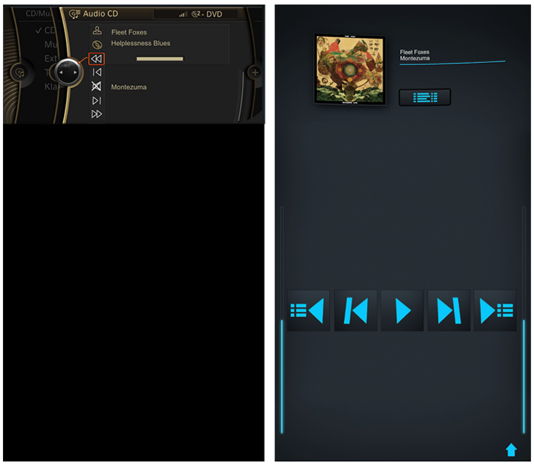

Figure 4.3: Comparative interfaces of state-of-the-art approaches. From left to right: RemoteControl, SmallTouch.

impact on driving performance, visual distraction and task performance. The music player application had to be controlled while driving in a simulator environment. All five interface concepts were tested on the same prototype to avoid an influence of display position or image quality on the results.

Study setup

Participants 40 participants (31 male, 9 female) with a mean age of 28 took part in the evaluation. Due to corporate confidentiality rules, all of them were working for the BMW Group, but were not involved in the current research. All of them have a driving license. Participants were asked to indicate their level of experience with touch devices: 88% responded to use touchscreens of smartphones, tablets or ticket machines at least once a day. More specifically asked for the context of the car, 15% reported a daily usage, on either integrated or attached navigation systems, or brought along nomadic devices such as smartphones.

Task The given task was to control a music player application integrated in the infotainment system. Six different sub tasks – *play*, *pause*, *skip song forward*, *skip song backward*, *skip playlist forward* and *skip playlist backward* – were performed following the announcement of pre-recorded audio commands given through additional speakers next to the participant.

Conditions To evaluate the three different interfaces described above (*SpaceTouch*, *KnobTouch*, *SwipeTouch*), we compared them to two commonly applied interfaces (see Figure 4.3). The first is a remote controller interface (*RemoteControl*) similar to the current BMW iDrive system. Functions are displayed in a vertical list, with a pointer indicating the currently selected function. The controller which is placed horizontally in a comfortable position in the center console can be turned left and right to navigate in the list, and is pressed to choose the current selection. If the knob is turned further when the last entry is reached, the pointer remains at the last position, and does not jump to the other end. The controller can also be pushed towards the left, right, top and bottom, but this is used for menu navigation, and thus not utilized for music player functionality. The second comparison interface, *SmallTouch*, is a touch interface based on a standard button size of 30 x 30 mm (9.0 cm^2). This was inspired by Colle and Hiszem [46] who recommend a size of 20 mm when using a kiosk standing in front of it. This size was further increased to compensate for car movements and vibrations.

Study design The study was conducted in a dual-task scenario. As their primary task, participants followed a car on a multilane road in a distance of 50 m at a speed of about 100 km/h. This task was announced to have priority over all other tasks during the study. The secondary task was to control the music player application. We chose a balanced within-subjects design to reduce the impact of individual differences, regarding experiences with the usage of touchscreens while driving, and also regarding experience with simulator studies. The order of execution was counterbalanced using a Latin square. For each interface, participants were given 18 tasks to control the music playback. The order of tasks was randomized, with each task occurring equally often, and *play* always following *pause*. To test for the effects of successive selections, two of the 18 tasks were adjusted to ask for multiple adjustments (e.g. *three songs forward*).

Apparatus The study was conducted in the usability lab of BMW Research and Technology. The driving simulation was realized with the simulator software SPIDER [276]. The street scene as well as an emulated head-up display for speed indication was displayed on three 42” screens in front of the participant. The hardware mock-up (see Figure 4.4) consisted of a steering wheel, instrument cluster, seat and pedals. Input and visual output for the secondary task was realized on the 17” touchscreen in the center stack and a multifunctional knob in the center console. On the screen, a (non-functional) knob of 42 mm diameter and 12 mm height was attached. For the interface using the remote controller, only the upper part of the display was used, which corresponds to the display space available in current cars on the market. For the analysis of glance behavior, the glass-based Dikablis eyetracking system by Ergoneers[45] was used. To be able to assign glances to relevant areas in the field of view, infrared-based marker boxes were attached to the mock-up. The application running the different interfaces was developed with Adobe Flash CS5. It was also used to track secondary task performance.

Procedure The evaluation started with setting up the Dikablis system. Participants put on the eyetracking glasses and performed a calibration. Then, the driving task was introduced, followed by an accommodation phase in which they practiced to follow the front car with the correct distance. In the meantime, it was verified that the eyetracking system was working properly. After that, participants were introduced to the setup and the task of controlling the music player application. They were presented with the first interface and were asked to try every function at least twice until they felt familiar. The driving simulation was started, and as soon as the car-following task was established, they were given the instructions on how to control the player. The researcher observed the task completion and took notes of unexpected occurrences. Afterwards, a questionnaire capturing subjective workload, perceived usability and user experience was completed. Then, the next interface was introduced. After all interfaces had been completed, a semi-structured interview was conducted to capture problems, preferences and general feedback. Overall, the study took about 75 minutes. Everything was videotaped for later analysis.

[45] `http://www.ergoneers.com/de/products/dlab-dikablis/overview.html` [cited 2013/11/15]

Figure 4.4: Simulator setup for the *SimplePlayer* evaluation. a: Mock-up b: Visualization of KnobTouch on the 17” touchscreen. Below, the iDrive controller for RemoteControl is attached.

Independent and dependent variables The independent variable was the *type of interface* that was used to control the music player application. Visual distraction was measured with the eyetracking glasses. Additionally, primary task performance was measured as lateral and longitudinal position, and secondary task performance as task completion time and error rate. Moreover, subjective feedback was collected regarding perceived usability (SUS [32]), workload (NASA TLX [96]), user experience (AttrakDiff [99]) and user preference.

Hypotheses

H1: Visual distraction can be reduced using spacious buttons and kinesthetic perception.
H2: Visual distraction can be reduced by providing a haptic orientation point.
H3: Visual distraction can be reduced using position-independent touch gestures.

Results

Because of problems with the touch recognition we observed during the study, some data sets had to be excluded from the analysis. Results are based on the remaining 3542 tasks. The results are reported at a significance level of .05.

Task completion time The measurement of task completion time started when the task was indicated and ended with a successful selection. Performing a single task, task completion time was significantly influenced by the interface used (significant by an ANOVA: $F_{1,3135} = 5.84$, $r = .33$). A post-hoc Wilcoxon test with Bonferroni correction revealed that SpaceTouch ($m = 2.17$, $sd = 0.43$, times in seconds) allowed for significantly shorter interaction times, while RemoteControl ($m = 2.48$, $sd = 0.79$) and SwipeTouch ($m = 2.53$, $sd = 0.71$) significantly increased it. There was a significant influence of the task that was performed for the remote controlled interface. Play always succeeded pause, and because those functions were alternating and at the same position in the function list, the pointer was already in the correct position (play). As a result, play was performed significantly faster than pause for RemoteControl ($F_{1,78} = 27.52$,

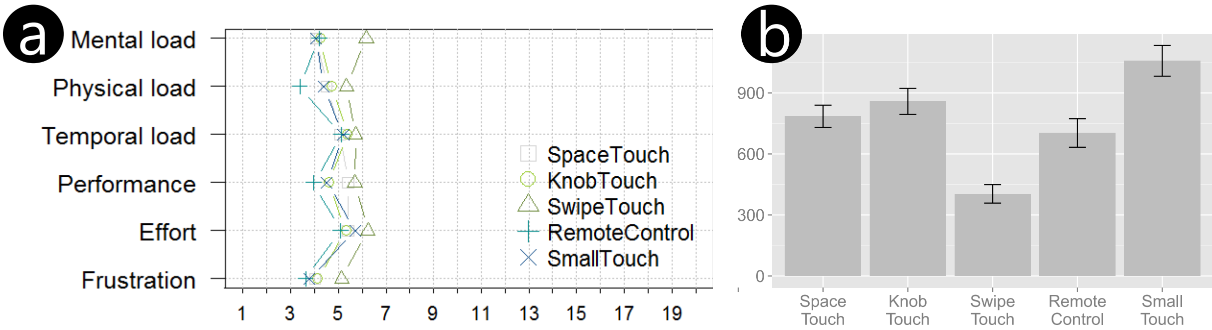

Figure 4.5: Trade-off between mental and visual load. SwipeTouch has the a: highest NASA TLX mental workload rating but b: on the other hand the shortest accumulated glance times.

$r = .63$). For succeeding selections (e. g. "skip three songs"), there was again a significant effect of the interface ($F_{1,350} = 8.85$, $r = .41$). Pairwise comparisons reveal a significant difference between SpaceTouch ($m = 4.16$, $sd = 0.83$) and SwipeTouch ($m = 4.62$, $sd = 0.91$).

Error rate The overall number of errors was low. Errors for RemoteControl occurred when the wrong function was chosen from the vertical aligned functions. Using SwipeTouch, errors occurred mainly because participants chose the wrong swiping direction. In the remaining direct touch interfaces, there was an increasing number of errors, mainly misplaced touches, when the touch areas were smaller.

Usability All systems were rated positively with mean SUS ratings between 78 (SwipeTouch) and 86 (SpaceTouch, KnobTouch) (out of 100). A Friedman test revealed a significant effect of the used interface on how quickly the system could be learned (SUS7) ($X^2(4) = 27.31$) and how much had to be learned (SUS10) ($X^2(4) = 31.17$). Post-hoc tests revealed that RemoteControl (SUS7, SUS10) and SwipeTouch (SUS7) were rated significantly worse than SpaceTouch and KnobTouch. Moreover, RemoteControl is rated as more complex, compared to SpaceTouch and SmallTouch ($X^2(4) = 14.74$). On the other hand, RemoteControl received a better rating on perceived confidence than SmallTouch and SwipeTouch ($X^2(4) = 12.91$).

Subjective workload All interface were rated to create a low to medium workload (25 - 34 of 120). There was an effect of the used interface on physical demand ($X^2(4) = 14.56$), but there were no significant post-hoc test results. RemoteControl was rated to be least exhaustive.

Visual distraction Due to tracking errors, some data sets had to be excluded from the analysis; to keep a balanced experimental design, the data of 25 participants was used for the analysis. Mean glance duration was lowest with SwipeTouch ($m = 0.40$, $sd = 0.40$) and RemoteControl ($m = 0.70$, $sd = 0.74$) (see Figure 4.5). Those were significantly shorter than all other interfaces ($F_{4,1796} = 70.21$, $r = .86$) Subjective ratings on perceived visual distraction support the eyetracking data ($X^2(4) = 49.31$). Regarding the number of required glances per task, 34.7% of tasks with SwipeTouch were performed without a glance, in contrast to 28.0% with RemoteControl. KnobTouch showed the highest number of tasks performed without a glance of all direct touch interfaces (9.9%).

Driving performance Driving performance was measured with data taken from the driving simulation. Lane keeping was assessed as the mean lateral deviation from the road center [154]. There was no significant difference between the interfaces ($p > .05$, $r = .10$). Moreover, the deviation from the optimum distance between simulator car and lead car was used to observe if drivers reduced their speed "in order to cope with the demand from the interaction with the secondary task" [97]; again, no significant effect was found ($p > .05$, $r = .12$).

User experience User experience measures show high pragmatic (PQ) and medium to high hedonic quality (HQ). SwipeTouch was rated high regarding HQ, influenced by its new and most innovative modality, which made it "fun" to use; however, it provoked many ideas for improvement and showed the worst technical performance. The good HQ of KnobTouch was commented to result from its visual design as it "looks nice, aligned around the knob". SpaceTouch with its large buttons performed best regarding PQ.

4.2.3 Interpretation & Discussion

The results on visual distraction show that **H1** (*Visual distraction can be reduced using spacious buttons and kinesthetic perception*) has to be rejected. Despite the large button size, glances were required to locate the respective functions on the large screen. The increase in size of SpaceTouch compared to SmallTouch had a positive effect on task completion time and visual distraction. Furthermore, the results of SwipeTouch provide support for the general idea of blind localization of large areas. Two regions for horizontal swipes were defined to control either songs or playlists, and those could mostly be controlled with either no or only one short glance. Asking participants for their preference while driving or when stationary, SpaceTouch was rated better in the dynamic condition. This is supported by comments that highlight the usefulness of imprecise targeting while driving, but also that it is a waste of space when the driver can fully concentrate on the interaction. Advantages of the direct touch paradigm arise regarding task completion time and perceived learnability and complexity.

Compared to SpaceTouch, KnobTouch shows a slightly greater number of blind interactions, but there was still a high number of interactions that were accompanied by glances, so **H2** (*Visual distraction can be reduced by providing a haptic orientation point*) has to be rejected. It is promising that single participants successfully tried to first approach the haptic knob element and locate the respective touch button from there without looking at the screen. Moreover, we observed that additional haptic orientation points such as the screen's border can support the orientation as it has been reported by Hausen et al. [100]; buttons closer to the border were easier to locate than "inner" elements because the border could be used as a reference frame.

Confirming previous research [10, 210], SwipeTouch showed a low amount of visual distraction. More than one third of commands was performed with no glance using SwipeTouch, even though it was not designed to be completely arbitrary where to start a touch gesture, so **H3** (*Visual distraction can be reduced using position-independent touch gestures*) is accepted. We confirm that touch gestures should be used for a limited function set to allow for simple, easy-to-perform gestures. Position-independent gestures such as the up/down-swipe which we used for play/pause have proven to prevent visual distraction, but we also showed that the function set can be extended by applying simple gestures to different, sufficiently large areas. The drawback of touch gestures is their mapping to functionality. Despite the results of Pirhonen et al. [210] but in line with Burnett and Porter [37], we experienced interaction errors due to confusions of swiping directions. It seems that the mapping between directions and functions is strongly depending on former experiences. "Skip forward" was related to a forward, left-to-right movement towards the respective icon, while "skip backward" was mapped to a backward, right-to-left movement. Participants mainly divided up in two groups; those who had and those who did not have experiences with Apple's cover flow. There, a swipe in the opposite direction is required, to "fetch a cover from the right" with a movement to the left. This did not appear consistently, though; some participants mentioned that because of the graphical user interface, it was especially clear that the direction was inverted. We conclude that with changing experiences of touch gestures, interfaces have to be designed carefully and robust to similar applications. Figure 4.5 depicts the trade-off we observed regarding visual and mental workload for SwipeTouch. We believe that this is due to the confusion of touch gestures. The increase of mental workload seems lower than the decrease of visual distraction, and we did not find that there was an impact on driving behavior. Still, the overall goal should not be to shift distraction to a different domain but to lower the overall level of distraction.

Participants highlighted the flexibility of a screen based solution in comparison with physical controls. It provides the possibility to switch modalities depending on the situation and to combine direct and gesture-based touch interfaces to provide a redundant access to functionality. Global touch gestures can be added as an overlay to touch interfaces [10], so the user can use the modality that fits best to the current situation. This requires to indicate that touch gesture control is available unless they are used as expert functions that do not have to be apparent all the time. Those could also be configurable to control functions that are globally accessible. Apart from simple music player functions, they could be used to switch between domains; for example, a downward movement opens the player view, a movement to the right an overview of the traffic situation. In this way, they can serve as an entry point to different information screens in which further interaction is performed via direct touch.

Essence Touchscreens are increasingly integrated to control basic functionality while driving. Different approaches can be taken to ease non-primary interaction and reduce visual distraction. Touch gestures can be issued blindly, but mappings need to be distinct to avoid an increased mental load. In comparison with a remote physical control, direct touch is easy to learn and can reduce task completion time. However, it requires short orientation glances even with large button sizes. Those can be supported by hardware elements such as physical controls or screen borders, which narrow down the search space.

4.3 Distant interactive surfaces

Section 4.3 is based on: S. Rümelin, C. Marouane, and A. Butz. Free-hand Pointing for Identification and Interaction with Distant Objects. In *Proceedings of the International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '13)*, pages 40-47, New York, NY, USA, 2013. ACM Press [245]. The prototype was implemented by Chadly Marouane in the course of his diploma thesis [179], under the supervision of Sonja Rümelin.

Large displays can get out of direct reach for a user (Section 3.3.2). This is especially likely the case in the car, where regulations on hand-reach envelopes (Section 2.1.2) demand that the driver's shoulder should not be lifted off the seat during the interaction. With new display and sensing technologies, interactive surfaces will grow further, and they will be better integrable in the existing environment (Section 2.2.2). Not only traditional physical control elements, but also arbitrary objects in the surrounding can become interactive and trigger a reaction when interacting with them. Since the space in direct reach is limited, a way to interact with objects farther away is required. In office environments or home entertainment systems, a common way to interact with distant interactive surfaces and objects are remote controls, or by interacting with representations on a screen which is in direct reach. By identifying and manipulating those objects themselves without any additional tools or intermediate steps, direct interaction can be enabled. Therefore, the goal is to develop an interaction concept to directly access distant objects

4.3.1 *PointIt*: Direct interaction with distant objects

Approach: Deictic gestures

The interaction with screens in cars today is often performed via remote controls. The same applies for the interaction with POIs in the environment. The use of indirect control in a hierarchical menu can be cumbersome. To ease interaction and thus make it less distracting while driving, a set of simple, yet meaningful actions is required. Section 3.3.2 has introduced deictic gestures for a short and direct way to interact. Pointing can be used to identify objects and locations in the close but also in the more distant environment, and can also open up new ways of interacting with the ability to specify a certain direction.

Preliminary evaluation of pointing recognition and behavior

Before focusing on pointing use cases in the car, a preliminary evaluation was performed to analyze the feasibility of detecting pointing gestures, keeping in mind the specific characteristics of the car environment [179]. Several tracking algorithm approaches were investigated. Moreover, observations on pointing behavior were collected to inspire the definition of use cases.

Preconditions for the detection of pointing gestures There are specific conditions in the car that help robust pointing detection. Movements of users are restricted by the seating position so they can only move their hands, arms, shoulders and head. Interior pointing interaction is restricted to an area on the passenger's side of the cockpit which is visible without turning around. When pointing to an object outside the car, the pointing direction is restricted to the windows. First observations of people sitting in a car, pointing at markers inside and outside the car, further narrowed down the solution space: the direction that needs to be detected is defined by the vector between head and fingertip. This is different than in other contexts, where hand, forearm or arm vectors have been used [195], most likely because of the identified restrictions mentioned before.

Detection algorithm To increase the robustness of detection, it is assumed that the hand remains stable in the pointing position for a certain time. The positions of head and hand are determined to calculate a vector in 3D space that describes the pointing direction relative to a stationary sensor. A Microsoft Kinect, placed in the outer right corner of the front windows (see Figure 4.6) was used for depth and image recognition. A first attempt was based on the skeleton recognition provided by the OpenNI framework[46] that separates moving objects from the background and identifies them as a body part such as head or arm. For this method, it is sufficient to only see the upper body; however, the method fails as soon as fore- and background cannot be separated correctly. The second attempt isolated head and hand tracking. Based on the known characteristics (size of about 20 x 15 x 25cm) [82], the head could be easily identified in the predefined area of the depth image close to the headrest. For the hand position, a method provided by OpenNI was used that offers optical flow detection initiated by a waving gesture; however, this requires periodical recalibration. The final approach was based on the previous head tracking, and a related approach for the hand tracking. By scanning through the depth image, all neighboring pixels with depth values similar to the head are classified as user pixels. A pointing hand can be identified based on the height and width of the recognized blob as well as the pixels' distance from the head. This procedure is computationally intensive, but it is independent from frameworks or hardware and can, depending on the resolution of the depth sensor, be used to even detect small forefinger details.

Study design 18 participants took part in the evaluation. None of them was involved in the current research. Setting up the Kinect in the car, we experienced problems with the depth recognition, when objects such as the rear mirror were positioned between the driver and the camera. Therefore, the study was split into a lab and an in-situ part. A split-plot design as well as a between-subjects design for the independent variable setup (*lab*, *car*) was chosen. The inside dimensions of the 5 series BMW (see Figure 4.6) were replicated exactly in a lab setup, without the disturbing objects. On the one hand, this made it possible to validate the detection approach. On the other hand, we could gain experiences on pointing behavior in the actual context. The study consisted of three parts. First, participants were presented with city scenes, projected to the wall in front of them, where buildings were highlighted one after another. The task was to point until confirming audio feedback was played. Next, participants were asked to point at numbered areas on the cockpit surface as prompted. In the last part, participants experienced different recognition durations while pointing at an object in a city scene. After the practical

[46] `http:\www.openni.org` [cited 2013/12/21]

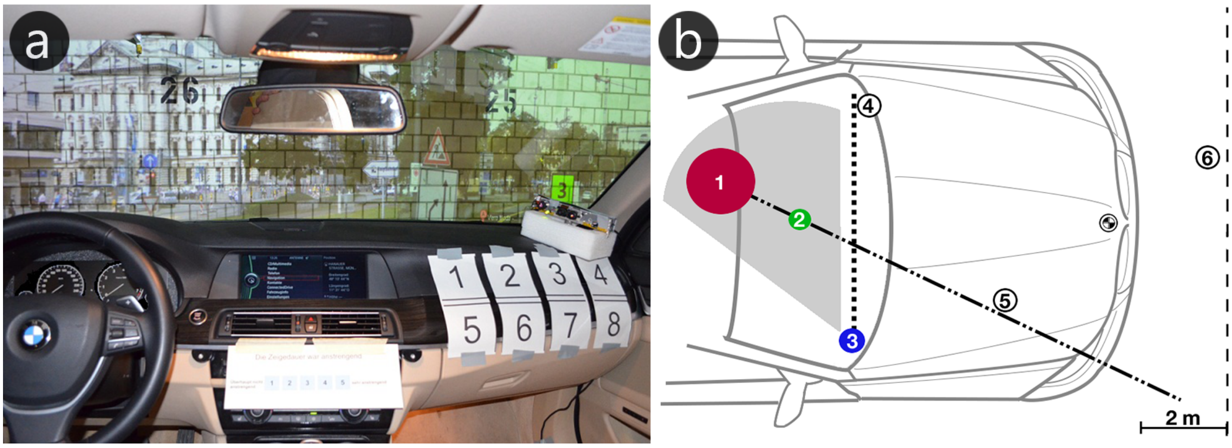

Figure 4.6: Study setup for preliminary pointing investigation. a: Setup inside the vehicle b: Technical setup (1. driver's head 2. pointing hand 3. depth camera 4. window area 5. pointing direction 6. projection plane).

part, a semi-structured interview on subjective impressions as well as potentials and challenges for pointing in the car was conducted.

The three street scenes we used contained 5 highlighted POIs each. The order of the scenes was counterbalanced for a repeated-measures design using a Latin square. The order of POIs and the eight numbered areas inside the car was randomized. To investigate tolerable pointing durations, required to unambiguously detect the gesture, 600, 800, 1000 and 1200 ms were used. Everything was videotaped for later analysis. The study took about 30 minutes.

Results & discussion The analysis of the recognition data reveals that for outside pointing, the separate tracking of head and hand as described above worked very well for the lab setup with an average hit rate of 95.8% (see Figure 4.7). It did, however, not work for the in-situ setup, where only 49.2% of targets were identified correctly. From the analysis of all video recordings, we believe that this is due to objects that occluded the Kinect's view, not because our tracking approach was erroneous. For the interior pointing, there were tracking errors for both setups because the interacting hand often got too close to the camera to be tracked correctly. Only 24.0% of attempts hit the target correctly; this was also due to the high number of possible targets in an overall small area. Regarding the tracking duration, we found that if the required holding time was shorter, participants rated it as more tolerable. For a robust tracking, 800 ms are required as a minimum; a paired-samples t-test did not show significantly different tolerance levels for 600 and 800 ms in the car ($t(8) = -0.32$, $p = 0.38$). Furthermore, the usefulness of the unobtrusive audio feedback was confirmed in the interviews.

Use cases

The preliminary evaluation showed first promising results that pointing can be detected unambiguously. Having people sit in the car and perform pointing gestures brought up ideas for potential use cases. In a next step, categories of use cases were worked out inspired by the comments

Figure 4.7: Exemplary visualization of pointing performance in the lab setup for pointing in the city scene.

of the study. Even though the analysis of the interior pointing data revealed recognition problems, we think that with an optimized camera position and more coarse-grained areas, it is a viable scenario.

Interior pointing For the interaction in the car's interior, not only controllers or displays that are in direct reach, but also objects further away can be interesting. This can be the glove compartment, objects such as a camera or a phone placed on the passenger seat or footwell, or, when thinking of increasing display spaces, outermost screen portions. Participants mentioned four different categories of use cases. Objects can be *adjusted* when pointing at them. For example, the passenger's window could open or close, respectively, when pointing at it. A related idea has been implemented in Audi's AR smartphone application eKurzinfo[47]: instructions and further *information* on control elements are displayed when pointing at them. The passenger's area was mainly associated with *storage* for rare or later use. One could place information on POIs but also digital content from the vehicle's infotainment system there, virtually or displayed on a screen in that area. The area and especially the glove compartment but also brought-along nomadic devices were considered as memory points in this case. The latter were also imagined to serve as a representation for another person for example planned to call during a drive. Distant space can also serve to *present peripheral information* which can be focused and brought closer by pointing at it, or it can be wiped away. Ambient information such as the traffic situation, presence indicators of nearby friends or favorite POIs were named.

Exterior pointing Possible pointing targets named were the external rear-view mirrors, but also a wide range of objects on or along the street, such as houses, street signs, scenes of accidents or other lanes. Similar to the interior pointing, *adjusting* objects out of direct reach, such as the outer rear view mirrors, was named. Moreover, *gathering information* on ambient objects was seen as a promising use case. Geoinformation systems (GIS) already hold information associated with location data, and applications such as Google Goggles[48] can recognize a broad range of objects such as vehicle models. They can present information on famous sights, or even translate signs. A more abstract association was raised with pointing towards the sky which could be used

[47] `http://www.audi.de/de/brand/de/erlebniswelt/audi_multimedial/audi_apps/audi-connect_und_mobilitaet/audi_ekurzinfo.html` [cited 2013-20-22]

[48] `https://play.google.com/store/apps/details?id=com.google.android.apps.unveil` [cited 2013-12-22]

to bring up the weather forecast. Going beyond presenting information, there could be *further interaction* with a selected object, for instance to call a number associated with a POI, or to "check in" with social services such as Foursquare or Facebook. Pointing at a street sign, the destination of the navigation could be set. Moreover, objects or associated addresses can be *marked* to be memorized for later use, to be shared in social networks, highlighting a specific property, such as an "accident" or a "nice spot". Finally, current navigation systems can only search for POIs around a position or along a route, but not for results in a certain direction. Pointing towards a particular cardinal direction where the user might remember a certain location, could serve as a *search filter* to narrow down too wide spread results.

Realization

Brainstorming sessions informed the design of use cases to be tested in a user study. For interior pointing, we selected the storage use case, while for exterior pointing, the provision of information and subsequent interaction such as calling, storing and marking were evaluated.

Three different scenarios were chosen in which pointing is used to interact with the infotainment system. In the first scenario, *RestaurantFinder*, the user has a certain idea of what to look for, namely a restaurant with a decent rating. By pointing towards a restaurant, ratings and further information are displayed, and subsequent interaction includes to call or save the associated telephone number. *SightCollector* allows to put together a sightseeing tour for a visiting friend. Pointing at a sight raises information on the name, opening times and entrance fees. Sights can then be added to the tour. The third scenario, *ImmoScouter*, is based on the idea that the user is looking for a new flat. When using real estate websites, people can set various filters to get a list of objects. A pointing-based way is to drive around a target area and point at appealing houses to get further information, such as if there are flats available. Moreover, characteristics to filter future searches can be identified. In a second step, objects can be saved for later review. To save selected POIs, two ways of interaction are possible; either the menu on the central display can be used in combination with a remote controller, or a follow-up gesture by can be issued, so by pointing towards the glove compartment on the passenger's side, the POI is "stored" there.

4.3.2 Evaluation – Pointing while driving

Having verified that there is a promising recognition approach using head and hand position to identify the pointing direction, we wanted to put the use of pointing gestures in a real-life context and thus conducted an in-situ driving study, where people were asked to use pointing gestures while driving. Three different scenarios where pointing is used to interact with objects outside and inside the car were investigated with a focus on acceptance and applicability of pointing in the car, as well as the effect on driving and glance behavior.

Study setup

Participants 15 participants (13 male, 2 female) with a mean age of 27 took part in the evaluation. All of them are working for the BMW Group but were not involved in the current

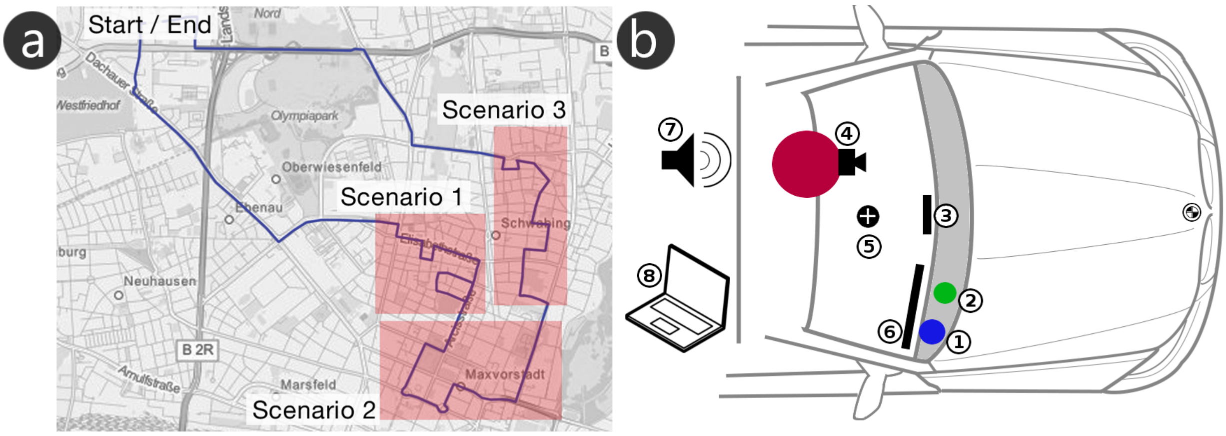

Figure 4.8: Driving study. a: Route sections for the different scenarios. b: Technical setup in the car (1. Kinect sensor 2. video camera 3. central information display 4. eye-tracker 5. remote controller 6. storage area of the cockpit 7. speaker for audio feedback 8. laptop for wizard-of-Oz input).

gesture research. All of them had undergone an internal driving training which ensured that they could react safely in case of critical situations during the study. On average, they were driving 10000 km per year, and predominantly characterized their driving style as calm. Two of them were left-handed. All except one participant were already familiarized with the use of a CID in combination with a multifunctional remote controller. About half of them were using location-based services (LBS) on a regular basis to search for locations such as shopping or parking spaces or for interesting places in general.

Task Participants had to perform tasks corresponding to the three usage scenarios. With the *RestaurantFinder* scenario, the task was to find a nice looking restaurant with a rating of 4 stars or higher. Moreover, the participant should make a reservation in a given restaurant for the next evening by calling the associated number. For the *SightCollector* part, the goal was to create a sightseeing tour consisting of up to ten POIs, and share one of them in a social network. In the *ImmoScouter* scenario, the task was to select several interesting buildings, and in the end to delete the first saved entry.

Conditions For most tasks, pointing was the only available modality. If a follow-up interaction was possible, it was performed with either another pointing gesture or via the remote controller in the center console.

Study design A within-subjects design was chosen to collect each participant's feedback on every scenario. We decided to use one route layout for all participants (see Figure 4.8a). The goal of the study was to gather qualitative insights rather than deciding if one scenario was better than the other, hence the lack of counterbalance. In the first section of the route, participants could get used to driving and to the pointing gesture. Later, each scenario was fitted to a specific section of the route where restaurants, sights and nice houses, respectively, could be found easily, and that included parking lots for the interviews after the completion of each scenario. The use of controller and pointing for storing a POI was alternated.

Figure 4.9: Screenshots of the prototype application. Top left: The system is continuously searching for a new pointing gesture. Top right: As soon as a pointing gesture is detected, a geodatabase such as Qype is checked for available object data. Bottom left: Available information such as opening hours can be presented. Bottom right: The object can be tagged and forwarded.

From the results of the preliminary study, we had found that pointing recognition in the narrow cockpit area of a vehicle did not work properly with the Kinect. A further restricting factor was its vulnerability to the sunlight's infrared components that could not easily be filtered out in our test car. Therefore, we decided for a *wizard-of-Oz* study in which the tracking module of the application was replaced by the investigator in the rear part of the car. Attention was paid to make sure the wizard's recognition performance was similar to the results of the lab study.

Apparatus The study took place in a BMW 7 series vehicle. According to the wizard-of-Oz methodology, we set up all hardware components for gesture recognition as if everything was working (see Figure 4.8b). Next to the Kinect sensor on the front right dashboard, a video camera was placed to record the driver from the front. Moreover, the driver was equipped with a Dikablis eye-tracking system from Ergoneers[49]. Its glasses integrate two cameras. One is directed at the pupil of the right eye to track the viewing direction. The other one is directed towards the field of view of the person wearing it. As a result, it gives back a live stream of images in which the spot the person is looking at is highlighted in the front view camera image. Informal preliminary tests had shown that with this video stream and the view from the back of the car, the wizard could identify the objects chosen for pointing accurately. They were then selected by him on a map application that sent the respective information to the car, which in turn was presented on the CID. Since we wanted to integrate our application seamlessly into the on-board system to make it feel like a realistic feature of the car, we decided to match layout and main interaction features to the latest iDrive system (see Figure 4.9). The main interaction during the study was performed via pointing. In all other use cases, rotating and pressing of the controller was used.

Procedure Participants took part in the study individually. First, they put on the eyetracking glasses and performed a calibration. Moreover, to make the tracking credible, the gesture recog-

[49] `http://www.ergoneers.com/de/products/dlab-dikablis/overview.html` [cited 2013/11/15]

nition setup was calibrated. Before starting the tour, participants were instructed to think aloud to get "live" feedback on the situations. After that, participants could explore menu navigation and pointing. They were provided with audio feedback when a gesture was recognized. The study was conducted while driving in normal day-traffic in Munich. The investigator was sitting in the rear part of the car and gave all navigation instructions. After about 10-15 minutes of getting used to driving, the first scenario, *RestaurantFinder*, started. After finding a highly rated restaurant, participants were instructed to find a given crêperie and initiate a phone call to make a reservation. Then, a short structured interview was conducted. The second scenario, *SightCollector*, took place in the museum quarter. Afterwards, a further structured interview phase took place. Before starting the next scenario, the participant was asked to share the last selected sight marked as "nice spot" in Facebook. In the third scenario, participants were driving through a residential area. For saving a POI in *ImmoScouter*, they either used a pointing gesture to the glove compartment area, or the remote controller for menu navigation. Every participant used each option three times subsequently, the starting order was alternated. After the subsequent structured interview, they were asked to delete the first entry. The study was closed with a semi-structured interview about the system as a whole. Positive and negative experiences during the study were collected and questionnaires on user experience and demographic data was completed. The whole study lasted for about 90 minutes.

Independent and dependent variables Driving behavior was measured in terms of speed taken from the car's internal CAN bus. Subjective feedback was assessed through semi-structured interviews, a short version of the AttrakDiff [99] and further comparing questions. Driving and pointing behavior was observed from the rear seat as well as in the video analysis. Different typical types of detection errors were included to imitate a realistic scenario. Pointing was either a) not recognized at all, b) did not give a result or c) gave too many or wrong results. Every participant experienced each error at least twice. Questions were asked on the fault tolerance.

Hypotheses

H1: Pointing while driving does not have a negative impact on driving behavior.
H2: Pointing is easy to learn and useful in the given scenarios.
H3: Continuous use of the same modality is preferred to changing modalities.

Results

Results are reported at a significance level of .05.

Subjective distraction Participants rated their subjective impression on distraction while pointing on a 6-point Likert scale. Especially the second scenario, putting together a sight seeing tour, was said to be realistic, and the spontaneous interaction was simple. The second and third scenario were rated less distracting than the first which may either be caused by the scenario, or by the order we did not counterbalance. Restaurants in the first scenario were sometimes hidden in a row of shops and stores. In contrast, the second and third scenario asked for the selection of arbitrary large objects that might have been easier to localize. Analyzing the single interactions steps required for pointing revealed significant differences regarding their potential to distract ($X^2(2) = 8.71$) (see Figure 4.10a). A follow-up Bonferroni test showed that the first step, searching a POI, caused significantly more distraction than the second step, pointing at it.

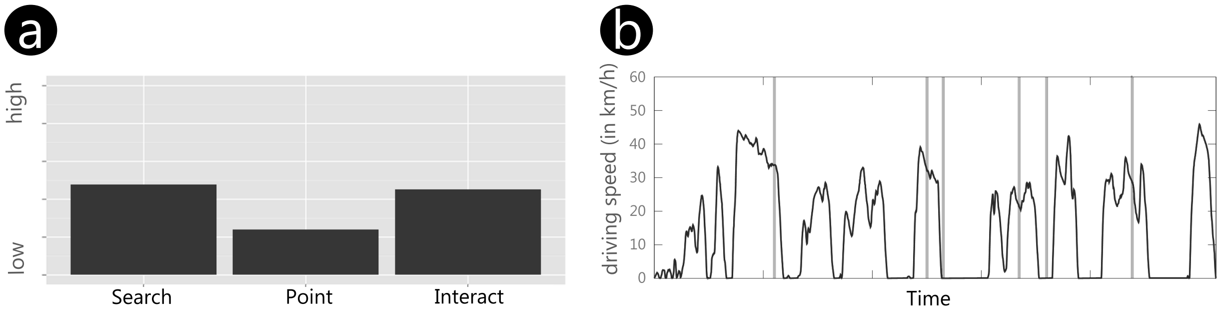

Figure 4.10: a: Perceived distraction in the different interaction steps. b: Visualization of driving speed while pointing. The vertical bars indicate pointing events.

Comparing the use of a pointing gesture to the glove compartment area to menu interaction with the remote controller for the saving task, a Wilcoxon test showed that perceived distraction is lower for gestural interaction (t = 5.00). Asked for their preference, all participants agreed on the pointing gesture although most of them were experienced with controller interaction and the gesture did not provide haptic feedback. Benefits were 1) the seamless connection to the preceding selection process, 2) that there was no need to change the modality between selection and saving, and 3) the easy learnability as the idea of storing something in the glove compartment area was immediately clear.

Driving behavior Results on driving behavior are based on CAN speed samples taken every 200 ms in the second scenario. Here, participants were more accustomed to pointing than in the first scenario, while in the third scenario, driving speed was very low as the route took the drivers through a quiet residential area. Overall, the analysis is based on 97 gestures. Most of the time, pointing was executed while stationary or rolling slowly. Participants slowed down before or during performing the gestures (52%), or they kept their current speed (33%). In the remaining events, speed increased slightly. Figure 4.10b visualizes the driving speed over time for one participant.

Glance behavior Similar to the phases of movement of the hand when pointing (moving towards, remaining still, moving away; see Section 3.3.2), there were three phases in glance behavior, the last of which was often skipped. Before the actual gesture, an information glance is performed by focusing on the object that is to be selected. Then, the arm is moved to point towards that object. A second controlling glance is performed to ensure this position is correct. Therefore, the visual focus is on the object again and it is checked that the fingertip is positioned in the line of sight. If necessary, the arm's position is adjusted. In 43% of all cases, the interaction was finished here. Otherwise, a further control glance was executed that followed the same procedure as the first one. For the interior pointing, when a POI was saved, there were significant differences in glance behavior regarding gesture or controller interaction. 75% of the gestures were confirmed with one control glance. In the remaining 25%, participants did not look at all while performing the pointing gesture. In contrast, controller interaction mostly provoked one or two control glances (48% each).

Error acceptance Asked whether one of the three types of errors described above would discourage them from using the system, participants showed a high fault tolerance. The most

Figure 4.11: Process of pointing while driving. Users are first looking towards the object they want to select (left). Then, they bring their arm into the pointing position and hold it there (middle). A second and sometimes third glance is used to ensure the correct arm position (right). After that, the arm is put back to the steering wheel.

serious error would be if pointing was not detected at all, which would prevent 13% from further using the system. Recognition of no or wrong objects was affecting the level of tolerance less (7% each). When multiple objects were recognized, a list was displayed, which participants suggested should be enhanced with images of the objects.

Suitability of pointing To assess whether the unique feature of interacting directly with the environment provides an advantage over existing applications, participants were asked to compare pointing to the LBS that are integrated into latest car generations. Taking the example of Google Local Search which was familiar to all participants and which was demonstrated via printed screenshots, participants rated the usefulness of both pointing and the LBS. The preferences depend on the use case; overall, a combination of both was suggested. LBS were favored for planning ahead, as in the POI search in the first scenario. Pointing was favored for the spontaneous interaction with an object nearby such as in the second scenario. Here, the direct interaction can help to associate information with a POI and memorize it.

User experience Both measures of user experience, hedonic and pragmatic quality of the system, were rated high. Pointing was said to be a useful and usable tool to select objects or to specify an action, and allows to directly express one's information need.

4.3.3 Interpretation & Discussion

The wizard-of-Oz design was a limitation that we accepted to evaluate different scenarios for distant but direct interaction. Refined depth cameras such as time-of-flight (TOF) cameras [60] are less vulnerable to sun light. Our detection approach seems robust and with the further improvement and integration of gaze trackers for the car environment [143], recognition results might even be improved.

The pointing process, as depicted in Figure 4.11, did not affect the primary task performance negatively, so **H1** (*Pointing while driving does not have a negative impact on driving behavior*) is confirmed. Drivers adjusted their speed when pointing gestures were used, or they pointed while the car was standing. Participants did not think that their driving performance degraded when pointing because the glances needed for pointing did not tear their visual attention off the road "for more than a short glance". Adjusting speed seems to be a subconscious action that is not disturbed by the pointing gesture itself. The search phase and focusing on objects was commented to be more distracting than the gesture itself, but also described as a normal behavior while driving. Slowing down was said to be a common compensating strategy and should therefore not introduce new safety issues. The analysis of glance behavior showed that for most pointing gestures, two short glances before and after positioning the hand are directed towards an object to be selected, with an occasional third glance to verify the result. The time in-between was used to monitor traffic. Interior pointing towards the large passenger's area was accompanied by one or in 25% of cases even no glance.

Pointing was considered as useful in the given scenarios where POIs could be selected to get further information, or to store them for later use. The direct selection was regarded as a natural way to interact with the environment inside and outside the car, so **H2** (*Pointing is easy to learn and useful*) is accepted. Drivers point at POIs already; this might only become critical when people outside misinterpret a pointing gesture. This did not happen during the studies and it also did not appear to be a problem that the pointing direction had to be adjusted during the pointing procedure because of high speed or close distance.

The seamless transition of consecutive pointing gestures was estimated as a positive feature. Modality switches of manual input should be avoided; however, speech input was regarded as a promising extension of the system, to lead to an even more natural interaction. Therefore, **H3** (*Continuous use of the same modality is preferred to changing modalities*) is neither confirmed nor rejected, as it depends on the characteristics of the used modalities.

Essence

In this project, we investigated pointing for the interaction with interactive objects out of direct reach. The car setting helped to create a robust detection approach for simple pointing gestures.

Pointing gestures can be used to identify objects outside and to interact inside the car. Seamless consecutive gestures are most suited for spontaneous interaction, to complement with LBS for planning ahead. In an in-situ driving study, we found that users slowed down to compensate with the distraction which mainly emerged from locating the pointing target.

4.4 Dedicated interaction spaces

Section 4.4 is based on: S. Rümelin, P. Siegl, and A. Butz. Could you please... Investigating Cooperation In The Car. In *Adjunct Proceedings of the International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '13)*, pages 61-64, 2013 [247]. The prototype was implemented by Peter Siegl in the course of his bachelor thesis [269], under the supervision of Sonja Rümelin.

Infotainment systems in today's cars are mainly designed to be controlled by the driver, so the access is optimized for the use while driving. When driving together, however, the passengers are less restricted than the drivers. They can use both hands, and do not need to observe the traffic situation. Therefore, they can perform arbitrary demanding tasks, as long as this does not have a negative impact on the driver. To decrease the driver's workload, the passenger could take a more active role in managing the system.

However, passengers are not always considered as positive. A field study of Regan and Mitsopoulos [223] also revealed negative aspects; their presence and actions can be distracting, and passengers were said to be annoying if advising the driver what to do. The research question by Inbar and Tractinsky (see Section 2.1.2), "How [can] drivers transfer some of their tasks to passengers, while remaining in control?", goes even further as it asks not only to avoid negative but create positive experiences with passengers.

The goal is to develop a system that integrates both driver and passenger, and which allows the passenger to support the driver by carrying out a main part of the interaction. This aims to disburden the driver. Since such a support might also be regarded as negative by the driver, the system needs to be tested on how it impacts the driver's and passenger's perception of their respective roles.

4.4.1 *HelpMe*: Shared interaction for reduced driver load

Approach

We want to reduce the driver's load by providing the passenger with an own dedicated interaction space. There, the passenger can make use of the available manual, visual and cognitive capacities in a useful way, by supporting the driver with the in-car tasks. Scott and Carpendale [261] observed the social behavior when interacting together on shared tabletops. They found that dedicated spaces for individual and cooperative work are created to coordinate collaboration. This can help solving the problem of unintentional mutual touching as those spaces define the interaction that is performed there; personal territories are normally not invaded by others, while group and storage territories are intended to work together and to share resources (see Section 3.3.3). Orientation of content, which can be a problem for tabletop interaction when the involved parties face each other, is no issue when sitting side by side in the car's cockpit. Another topic for shared tabletop interaction which is relevant here is how to avoid unequal participation, if it results in

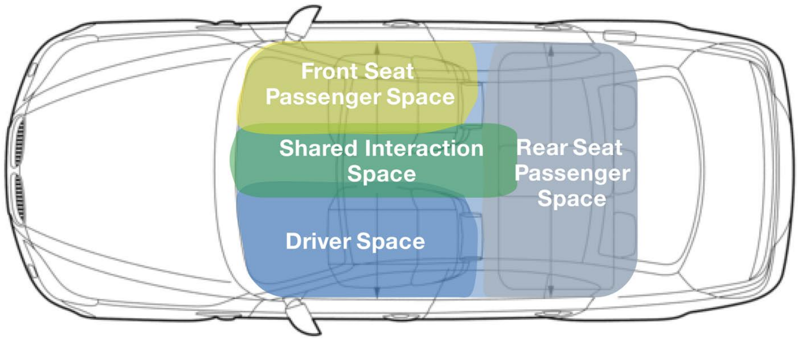

Figure 4.12: Interaction spaces in the car. Driver, front seat passenger and rear seat passengers have their dedicated interaction spaces. Moreover, shared interaction spaces can be created to support cooperation (figure adapted from [186]).

a discrimination of the weaker participant. The situation of the different parties in the car is not equal; the passenger can direct more attention towards the interaction with the infotainment system. However, the driver should still feel equally involved even if the interaction itself is performed by somebody else. Shared interaction spaces can serve as a synchronization point to keep everyone updated on the results of the interaction.

Use cases for cooperation while driving

We conducted a workshop with eight experts in the fields of interaction design, usability and engineering to define meaningful scenarios for driver-passenger cooperation. As a precondition, different user and interaction spaces were defined. Meschtscherjakov et al. [186] have set up a design space for the car where they distinguish driver, front seat passenger and rear seat passenger space. To integrate the theory of tabletop territoriality of Scott and Carpendale [261], we extended this with a further, shared interaction space (see Figure 4.12). The driver's dedicated space is set to be the instrument cluster and the HUD, while an interactive surface on the front seat passenger's side is called passenger information display (PID). The shared interaction space refers to the area of current CIDs. Then, we defined three different aspects of scenarios. First, there is the context: a shared ride can take place in a familiar or unfamiliar environment, in the city or on the motorway, at day or night or during a busy rush hour. Second, the relationship between the different parties can be family, partners, friends, acquaintances or colleagues, but also even less familiar such as in carpools or when hitch-hiking. Last, the topic or task that is dealt with influences the situation. Personal talks on friends or shared activities can lead to a navigation task, or activities with social media or the entertainment system; talking about the car's functionality might lead to adjustments or status checking. In the workshop, we set up an affinity diagram to identify reasonable combinations and jointly selected the most promising but also realistic ones:

Destination for a day trip: In an unknown city, a couple or close friends plans/plan a day trip while exploring the city. The passenger searches online for information, ratings and reports. The final selection can be transferred to the navigation system so that routing instructions are displayed in the driver space.

Looking for a bar in the evening: In their home town, colleagues are looking for a bar as their favorite one is closed. The passenger performs an online search, compares ratings and pushes selected information to the driver or shared interaction space.
Game about music: During a leisure drive, friends discuss on the music selection. They play for controlling it for the next half an hour. In games such as general knowledge questions or rock-paper-scissors, everyone has the most appropriate controls; the driver may use the steering wheel or voice commands, while the passenger can use both hands for touch input. The score is displayed in the shared interaction space.
Information on sights: In a foreign city, a couple is looking for information on sights in the surrounding. A map in the shared space displays POIs with some basic information, while in the passenger space, extended search on further details is possible; selected details such as pictures can be provided to the driver. After a selection, the navigation can be started or the POI can be saved.
Shopping list: During rush hour on the way to the supermarket, a couple or friends is/are planning for dinner. They want to select a recipe and set up the shopping list for it. Inspired by suggestions of an online search, meals and ingredients are displayed as pictures in the shared interaction space, while a more detailed view is provided to the passenger. The final shopping list in the shared space can be modified by both.

Realization

Through the prioritization of use cases, we found navigation use cases as the most promising application for cooperative systems in the car. *BankFinder* and *BarFinder* are designed to be used by either driver or passenger to display the respective POIs on a map. When a route is displayed, the proximity to it gives information on the required detour. Further details that can influence the decision such as opening times or ratings are displayed in a pop-up window. *TourPlanner* is designed as a joint sightseeing application that can be used to set up a route along various POIs. The passenger is able to get a more detailed view, whilst the shared screen gives an overview of chosen POIs on a map and in a list view, with the possibility for all parties to rearrange the order.

4.4.2 Evaluation – Cooperative POI search

Taking away power from a user, a patronizing effect might appear. From decision support systems it is known that when the support is subtle, the perceived control can be preserved [134]. On the one extreme, a system can leave the user in full control to decide everything. On the other extreme, a system takes over most of the control, which is for example preferable for novices who are unfamiliar with the task, while still leaving the user with the possibility to apply own knowledge. Overall, a system such as the latter may be more effective because the user is left with the perception of control, while time-consuming input and cognitive effort is not necessary. If the system now provides the passenger with extended functionality, the question is if the driver can keep the perception of control while being supported. We conducted a study to evaluate this acceptance of transferring responsibility to the passenger. For the driver, we set up a dual-task scenario, while the passenger could fully concentrate on the given tasks. The scenario was a shared ride, where two people had to find different POIs in a map-based application.

Figure 4.13: a: Hardware setup for the user study, running the TourPlanner application. On the center screen, the shared view is presented in which both driver and passenger can adjust the tour. On the right screen, the passenger view includes further details and more possible interactions. b: Arrow signs to which the driver had to respond via the numpad attached to the steering wheel.

Study setup

Participants Eight groups of two persons took part in the study (4 women, 12 men, mean age 28). All of the pairs knew each other beforehand. Friends and colleagues are reported to be the largest group of passengers after spouses and children, whereas foreigners only play a minor role [223]. 56% of our participants prefer to take the role of the driver, while the others prefer the passenger's role (13%) or are indifferent. The roles for the study were assigned randomly. All participants are driving in a car at least once a week in both roles and are using touch interaction on smartphones or tablets in their daily life.

Task For the interaction with the infotainment system, the three applications described above were implemented. With BarFinder and BankFinder, participants had to find a bar or a bank with certain properties and add them to the route. TourPlanner required them to set up a route consisting of at least five POIs.

Conditions BarFinder and BankFinder were controlled either by driver or passenger. The third use case was performed together.

Study design The first part of the study used a mixed design, where either driver or passenger (roles were assigned only once) searched for bars and banks; the order of the four combinations was counter-balanced. In the second part, driver and passenger used the TourPlanner application together to gain qualitative feedback on their cooperative behavior. The study was conducted in a dual-task scenario for the driver. For participants in the driver role, an additional primary task had to be completed to simulate a high-workload driving situation. A simple distraction task was deployed to keep their focus on the HUD, and therefore in the area where attention on the road is required. Similar to a lane change task, where drivers are asked to change lanes depending on signs along the road [180], drivers had to respond to highlighted arrow signs (see Figure 4.13b) as fast as possible on a numpad attached to the steering wheel.

Apparatus The hardware setup consisted of a steering wheel, a car seat for the driver and an additional chair of equal height for the passenger (see Figure 4.13a). Two 22” multitouch capable displays (Iiyama ProLite T2233MSC) were attached to form a shared central information display and a passenger information display. A 17” display (Asus VB175T) and a mirroring glass plate were used to simulate a HUD. The instrument cluster display was not used. Additionally, a numpad (Keyboard KL-368) was attached to the left side of the steering wheel. It was used by the driver to respond to the primary task.

Procedure Participants took part in the study in pairs of two. First, they were introduced to the scenario, driving together in a foreign city, and the main functionalities of the integrated system on the two screens. The driver was introduced to the distraction task and performed a test run. The study began by starting the distraction task. The experimenter gave the driver the instructions to find either a bar or bank with specific properties along the way, to be executed by the driver or to be forwarded to the passenger. After both parties had executed the tasks, they were instructed to put together a tour for the next day. During the study, the experimenter was present to answer questions and observe the participants’ behavior. The study took about 90 minutes.

Independent and dependent variables The independent variable was the *person* who was executing the task (driver, passenger). In between the tasks and afterwards, we conducted semi-structured interviews to assess subjective feedback on involvement and feeling of control in the different conditions. Drivers’ workload was assessed as distraction from the primary task, using reaction times as quantitative and subjective questions as qualitative measures. Moreover, subjective feedback was collected with questionnaires regarding perceived usability (SUS [32]) and user experience (AttrakDiff [99]).

Hypotheses

H1: The driver’s workload is decreased when the passenger supports.
H2: The driver’s feeling of control is increased when the passenger supports.
H3: The driver’s feeling of involvement remains the same when the passenger interacts.
H4: The passenger’s feeling of control and involvement increases when he can contribute.

Results

Results are reported at a significance level of .05. Subjective results are based on 7-point Likert scales. There were no differences between the results when using either the BarFinder and the BankFinder application, so the results are based on both tasks.

Perceived control After each task, driver or passenger were asked how they had perceived their control over the situation while one of them performed the search for a POI. The situation was specified to include both primary and secondary task. Figure 4.14a depicts that the drivers felt more in control when the passenger was executing the task. A t-test reveals a significant different rating ($t = -3.50$). We observed that performing both primary and secondary tasks led to confusion and errors of the driver, while there were no errors when the passenger was interacting. The passenger also felt to have more control over the situation when executing the task than when having a passive role. Moreover, the imbalance between the perception of driver and passenger was solved when the passenger was executing the secondary task ($t = 1.91$, $p > 0.05$) compared to

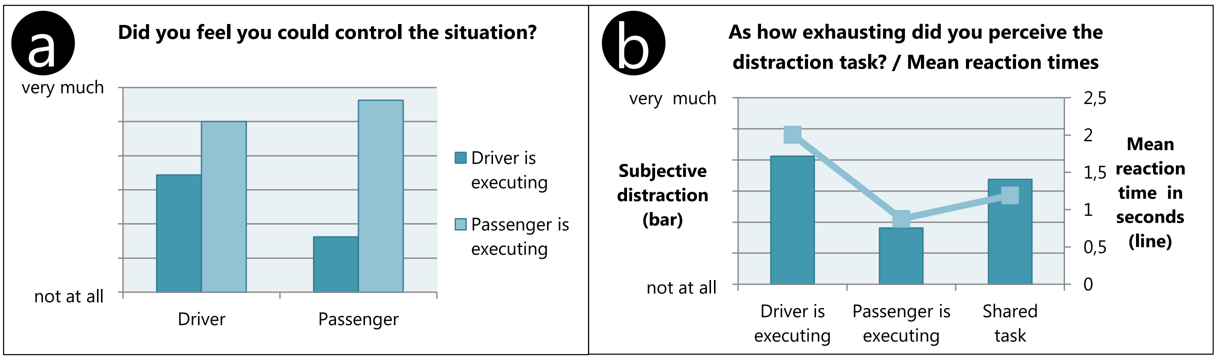

Figure 4.14: Results of the user study. a: Perceived control is better for both parties when the passenger is executing the tasks. b: Subjective and objective distraction is lower when the passenger is interacting or when the task is executed together (drivers only).

when the driver was executing it ($t = -3.27$, $p < 0.05$). Performing the TourPlanner task together, browsing details of POIs and selecting them was mainly performed by the passenger. Nevertheless, both parties had a good feeling of control, indicating that not only the direct interaction with the system is important. From observation and comments, the shared discussion on the selection and the possibility to influence the final selection and its order in the shared interaction space seemed to have raised the feeling of control for the driver.

Perceived involvement Asked how involved in the current situation driver or passenger felt, the one who just executed the respective task experienced a higher level of involvement. For the passengers, the difference between passive presence and active secondary task interaction was significant ($t = -6.65$). There was, however, no significant difference for the drivers ($t = -0.77$). Regarding the TourPlanner, both parties rated the involvement equally high.

Distraction Objective and subjective distraction measures indicate that performing both primary and secondary task, the level of distraction was increased compared to when the additional task was passed to the passenger (see Figure 4.14b). The driver reacted significantly slower to the events of the primary task ($t = 8.48$) and rated the perceived distraction significantly lower ($t = -5.20$). In the shared task, distraction only increased slightly.

Usability Results of the SUS showed high ratings for both driver and passenger, with slightly more agreement on potential usage for the drivers. Moreover, the analysis revealed higher ratings of ease of use for the passengers.

User experience Pragmatic quality of the cooperative system was rated high indicating that the functional goals that emerged were well supported. By providing the passenger with more information than the driver could handle, overall functionality can be increased, while an overview of the current status is constantly accessible for the driver. The hedonic rating showed a medium value, yet there is room for improvement. Due to the study setup, participants fulfilled pre-defined tasks rather than needs emerging from a real situation which did not seem to have an impact of the psychological well-being [98].

4.4.3 Interpretation & Discussion

Carrying out the study in a lab setting allowed us to control the primary task's difficulty. However, with a real driving task, the distraction level changes constantly, which might influence the results. Moreover, different levels of complexity of the secondary task might have an impact on the willingness to cooperate: while for very simple tasks the effort of handing it over might exceed the benefit, complex tasks are more likely to be handed over.

Objective and subjective measures of distraction show that the driver can concentrate better on the primary task if the passenger is supporting with the secondary task, so **H1** (*The driver's workload is decreased when the passenger supports)* is confirmed. We observed that it was especially important that the more passive person was still informed on what was currently taking place. Most of the people started commenting on their current actions to keep the other one up-to-date. Otherwise, the drivers sometimes neglected their primary task to sneak a peek at the passengers' display. It is important that the driver is not distracted by what the passenger is doing. However, from research on collaborative environments [280], we know that everyone should always be able to review the current status. This can for example be achieved by constantly displaying high-level results of the passenger's interaction to the driver.

Handing over the task in a situation with a high primary task demand did not degrade the feeling of control for the overall situation, but could improve it. The driver's subjective perception of control over the whole situation was significantly increased when the passenger supported, so **H2** (*The driver's feeling of control is increased when the passenger supports)* is confirmed, too.

The person who was actively performing the secondary task always felt more involved in the just experienced situation. Handing over the control to the passenger, the drivers' rating of perceived involvement only decreased slightly, so **H3** (*The driver's feeling of involvement remains the same when the passenger interacts)* is confirmed.

Cooperative interaction did not only improve the driver's perception of control, but it also had a positive impact on the passengers' perception of control and involvement, thus **H4** (*The passenger's feeling of control and involvement increases if he can contribute)* is confirmed. Furthermore, when the driver concentrated on the primary task and the passenger performed the additional secondary tasks, the imbalance of perceptions was decreased.

Essence

> Most automotive interfaces are designed to be controlled by the driver. Taking the passenger's capacities into account and assuming that the driver hands over upcoming tasks, the driver's distraction from the primary task can be decreased. Furthermore, infotainment systems can offer increased functionality.
> We did not find that the driver refused to transfer responsibility to the passenger to remain in control. In contrast, the findings of the study suggest that the design of cooperative systems can enhance the perceived control of both driver and passenger and raise the overall perception of involvement.

4.5 Lessons learned

With interactive surfaces, we are able to switch the interface depending on the current context. This can result in different information densities for driving and parking, or different interfaces for driver-only and driver-passenger situations.

The presented approaches are encouraging in that there are ways to control large interactive surfaces and spaces. Table 4.1 refers to Section 3.2.3 and points out that there is potential to reduce visual distraction compared to currently used touch interaction. Depending on the passenger situation, different concepts for interaction have been investigated.

For driver interaction with a reduced function set on the screen as in *SimplePlayer*, direct touch interaction could keep the overall task completion time low. On **spacious** interactive areas, unidirectional touch gestures could be issued blindly, but the mapping of functionalities to directions was difficult. Direct touch buttons could not be operated without occasional orientation glances. However, visual attention for the search task could be reduced by making use of kinesthetic perception and the provision of haptic orientation points.

To interact with **distant** interactive surfaces, pointing was regarded as a natural modality for a direct interaction inside and outside the car. We found promising use cases for the interaction with objects in the surrounding of the car, and for the use of the glove compartment to store virtual objects. The analysis of the *PointIt* prototype showed that pointing interaction depends on glances in the search step to identify targets and verify the pointing direction. However, regarding pointing gestures towards large predefined areas in the interior, 25% of the observed interactions were issued blindly, possibly due to a robust kinesthetic perception.

Dedicated interaction spaces for shared and passenger-only interaction on large interactive surfaces can be used to support the delegation of tasks from the driver to the passenger, to relieve the driver from performing input himself. Therefore, there is no need for localization and positioning. In addition, feedback can be provided orally by the passenger. Evaluating the *HelpMe* prototype, we did not find a negative influence on the driver's perceived control when the passenger took over responsibility, but in contrast a reduced workload of the driver.

		Visual attention required for			
Phase	**Task**	**Simple touch**	**Spacious touch**	**Distant pointing**	**Dedicated spaces**
Search	1) Localization	x	(x)	(x)	-
	2) Positioning	x	(x)	(x)	-
Selection	3) Input	-	-	-	-
	4) Feedback	x	x	x	(x)

Table 4.1: Improvements through large interactive surfaces to simple direct touch regarding visual distraction. Details can be found in the text.

Chapter 5

Shaped Interactive Surfaces

The last chapter has shown what types of interaction are possible with large, flat displays. If the driver is on his own, frequently used functions can be accessed quickly without a lot of visual attention. It is possible to access interactive elements even outside the direct reach, and if a passenger is present, rich interaction can be realized.

In case the driver's direct interaction is to be supported for more complex tasks, the search as well as selection tasks require further assistance to avoid visual attention towards the interactive surface. Localization and positioning in the first phase, but also rich feedback in the second phase require enhanced perception through other senses. Flat surfaces do not provide any features which the user can perceive non-visually. By modifying the surface structure, a richer haptic experience can be provided and haptic perception can be considered for the interaction.

Non-flat surface portions can raise the discernability of a surface. An everyday example are the raised structures on the F and J keys on a QWERTY keyboard. They make it possible to blindly identify the respective elements. A scanning behavior in combination with cutaneous sensing for the specific keys allows to position the fingers and thus enables eyes-free typing although the keyboard is a very complex input area.

MacLean and Enriquez' notion of "haptic icons" [176] highlights that opening up such a "new communication medium" [176] can enrich the feedback channel of interactive surfaces. Shaped interactive surfaces can contain such haptic icons. Therefore, this chapter will investigate whether such features can improve automotive touch interaction.

5.1 Preliminary considerations

To inform the exploration of shaped interactive surfaces, we conducted interviews with experts from the automotive domain to collect their experiences with the design of haptic interfaces. Experts with at least 3 years of work experience from different departments of a car manufacturing company, namely people involved with design, ergonomics, physical control elements, innovation strategy and HCI, were interviewed on topics that need to be considered when designing shaped interactive surfaces in the car.

General ergonomic constraints were named which are defined in regulations and standards (see Section 2.1.2). An example are hand reach envelopes which define the area in which the user can interact without the need to lift the shoulder off the seat, or the restriction of visually intensive interaction to an area within 30° below the line of sight. Controls outside the given viewing angle are required to be haptically distinguishable. Nevertheless, their visual design should also signify their affordance and include a visual representation of the assigned functionality on the contact face. They should provide both surface and control element haptics to support the different phases of interaction; from an ergonomic point of view, any haptic guidance can raise the user's confidence. The system should provide direct feedback within less than 250 ms, perceivable via both haptic and visual channel.

Moreover, a support for hand and finger was named to be essential. For a finger, this should have a depth of at least 15 to 20 mm. Convex shapes can be controlled more accurately, while concavely shaped elements can stabilize a finger that is placed upon it. Road holes or turns create forces than can lead to deviations of the interacting hand, and, as a result, operating errors. Expected movements are horizontal ones that are caused from steering actions, while vertical movements are less expected as they are caused by sudden bumps. This implies that control elements should be placed in a horizontal row, and they should be higher than they are wide, which is rarely applied in current designs. Regarding the optimal size of buttons, there was no definite answer. An overall width of about 2 fingertips is recommended which corresponds to approximately 20 mm; this width can be decreased when a row of buttons is separated with haptic barriers.

From a design point of view, smooth and clean surfaces are preferred. Moreover, large and horizontally oriented surfaces make the interior appear wide. To support driver orientation, the center console can be slightly tilted towards the driver side.

Overall, the experts agreed that many factors have an influence on the perceived usability of an interface: it has to fulfill basic functional properties, but a good design and a positive haptic appearance can also be convincing. Flexible assignment of functionality to physical controls is wanted to enable customization, unless it renders the interface incomprehensible.

5.2 Basic interaction

Section 5.2 is based on: S. Rümelin, F. Brudy, and A. Butz. Up And Down And Along: How We Interact With Curvature. In *Workshop 'Displays Take New Shape: An Agenda for Interactive Surfaces' in conjunction with the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*, 2013 [240]. The pyhsical prototype was built by Sonja Rümelin. The study software was implemented by Peter Siegl in the course of an internship, under the supervision of Sonja Rümelin.

Shaped interactive surfaces have their specific properties regarding overall shape and texture. However, other properties are shared with flat interactive surfaces. They offer the possibility to display content, and control them via direct touch input. In a first step, we wanted to investigate the differences of controlling interactive elements on either flat or shaped screen portions when executing basic tasks such as pointing or dragging, by enhancing the virtual controls with physical features.

5.2.1 Improving interaction compared to flat displays

Approach

From our design space for non-flat displays (see Section 3.4), we found that the effect of architectural curvature on direct touch interaction has not been investigated extensively yet. First evaluations have shown positive effects of surface shape on touch interaction when compared to a flat surface [95]. Surface orientation, in particular different types of curvature, provide different characteristics with regard to touch accuracy and interaction support [238]. By integrating curved surface portions, either concave or convex, the user is given features which can be perceived haptically. Compared to a flat surface this can potentially support the search phase and enrich the feedback in the selection phase (see Section 3.2.3).

To fit existing car interior geometries, we decided for horizontal bends with either concave or convex curvature. One can drag along, but also tap in (concave) or onto (convex) the respective peaks of the differently oriented bends. In-between, flat portions create un-distorted display spaces.

Use cases

Common controls in the car are direct switches such as those to switch on and off the radio or seat heating functionality. Often, functions that belong together are grouped and placed in a horizontal row, such as different buttons of the air conditioning (AC), driving assistance system or radio bookmarks. The control of continuous values such as volume, temperature, or fan strength is often realized with rotary controllers when using hardware controls, or with sliders when using touch interaction [181].

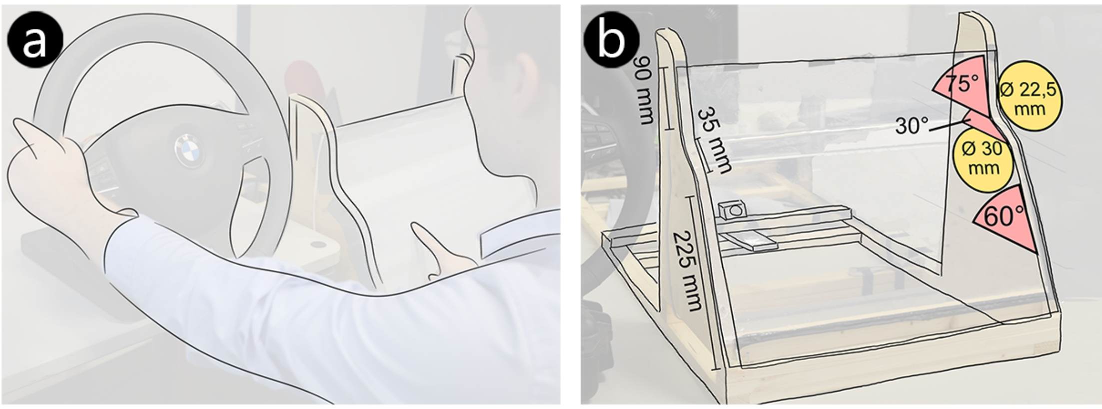

Figure 5.1: Rear-projected prototype realizing convex and concave bends. a: The prototype is intended to be placed in a center stack position. b: The prototype contains a camera and a projector in the back. The curved acrylic plate is enhanced with a silicon layer and a projection foil.

Realization

We set up three different tasks to investigate the effect of curvature on touch performance. *SimpleTap* simulates basic tap interaction. In the *RowTap* task, two buttons need to be tapped consecutively which are positioned next to each other. Physical buttons are often aligned in a row, enabling horizontal scanning behavior, for example when selecting a radio channel. If we feel that the touch position on the first button is askew, we can correct the position of the finger to touch the next button more precisely. The *SlideTouch* task is designed to evaluate the control of continuous values with touch sliders.

5.2.2 Evaluation – Tapping and dragging

To evaluate the performance when tapping and dragging on either a flat, convex or concave bent interactive touch surface, we built a rear-projected shaped display (see Figure 5.1). It was not possible to put this early prototype into a dynamic car or simulator environment, so we chose a static lab setting to gain first experiences.

Study setup

Participants 16 participants (12 male, 4 female) with a mean age of 27 took part in the evaluation. 63% were driving a car at least once a week, and more than 81% were using touch devices, mostly smartphones, at least occasionally.

Task SimpleTap was tested with five different approaching angles (-60°, -30°, 0°, 30°, 60°, see Figure 5.2) . The driver's normal starting point for interaction is the steering wheel. As a result, the hand's directional movement goes from the left to the right. To be able to control this approaching direction, a preceding tap at a given position on the left border of the interactive

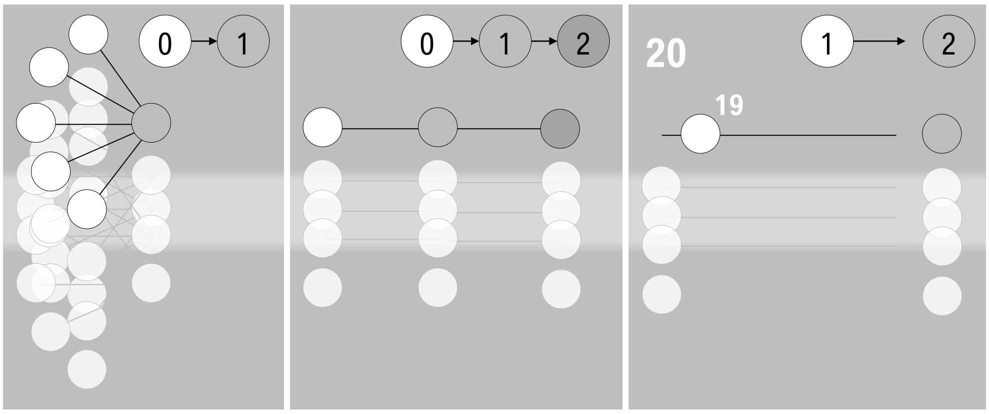

Figure 5.2: Task design for the user study. From left to right: SimpleTap, RowTap, SlideTouch. Details can be found in the text.

surface activated the task. This also prevented a possible occlusion of the target buttons from the driver's perspective. RowTouch was tested with two succeeding taps, again with a preceding tap to control the starting position. For TouchSlide, participants had to drag a slider to a given value (20%, 40%, 60%, 80% and 100%) and confirm the selection with a button on the right side.

Conditions The three tasks were evaluated for five different screen structures. Those were the two differently oriented bends as well as the three flat portions the prototype contained, above the upper bend, between the two bends and below the lower bend. Figure 5.2 depicts the tasks on the different screen portions. We used two different button sizes, with a diameter of 18 and 24 mm.

Study design A within-subjects design was used where all participants tested all tasks on every structure. The first two tasks were repeated after the third task, to capture learning effects. For each task, the order of structures and the order of sub tasks was randomized.

Apparatus Figure 5.1 shows the prototype of a shaped center stack, with touch functionality on its entire surface. There were some external constraints to its shape. It had to contain a display area located in the place of current CIDs, as glances there lie within 30° below the normal line of sight and distract the driver's view onto the street through the windshield only to a certain degree [47]. The lower part was designed to provide a large, comfortably tilted multi-purpose area in a good reaching distance. Transitions between these areas were realized as convex and concave bends.

To create the screen shape, 4 mm acrylic glass was bent using a hot-air-gun. Wooden battens were used to create the overall housing, to which the different components were mounted. The rear projected image was created using a laser projector (Microvision SHOWWX+) to enable a sharp image in the different depth planes. As a diffuser, we used light grey Rosco rear projection foil (not shown in Figure 5.1). An FTIR setup and a Pointgrey Firefly camera equipped with an IR filter lens were used for the optical touch tracking. On the software side, CCV 1.5[50] was used to convert the camera image into touch events based on the TUIO protocol [137] and a Flash application realized the user interface. During the study, participants were sitting in front of a steering wheel as in a car. The prototype was located to their right, simulating a center stack.

[50] `http://nuigroup.com/go/ccv15` [cited 2014/01/05]

Procedure Participants took part in the study individually. They were introduced to the prototype and were able to get used to it by dragging and zooming colored rectangles all over the screen. Then, they were advised to imagine a parking situation where they could direct their attention to the task completion; still, they were asked to keep their left hand on the steering wheel at a 9 o'clock position to ensure a consistent posture during the study. The right hand was used to solve the tasks. Participants were advised to solve tasks as quickly as possible, but primarily correctly. SimpleTap and RowTap were followed by SlideTouch, then SimpleTap and RowTap were repeated. After each task, subjective feedback was collected. In the end, a further, semi-structured interview was conducted. The whole study lasted for about 45 minutes.

Independent and dependent variables The independent variable *structure* contained five levels: the convex and concave bend and the three combining flat areas in different heights and with different tilt angles. Those were tested for three different *tasks*, SimpleTap, RowTap and SlideTouch. We used two different button sizes. Task performance was measured as task completion time. For each task on every structure, feedback was collected on the subjective impression of how quick, confident and comfortable the interaction on the different display portions was perceived. Overall feedback on usability and experience was captured with further comparing questions and the AttrakDiff questionnaire [99].

Hypotheses

H1: Pointing tasks can be performed with more confidence on structured display portions.
H2: SlideTouch can be performed with more confidence on structured display portions.
H3: RowTap can be performed faster on structured display portions.
H4: SlideTouch can be performed faster on structured display portions.

Results

Button size did not have a significant effect on the results, thus the following findings refer to both sizes. Task completion times are given as seconds. Results are reported at a significance level of .05.

Task completion time An ANOVA revealed a significant effect of structure for SimpleTap ($F_{1,1598} = 27.56$), with post-hoc pairwise comparisons revealing that the concave bend ($m = 0.76$, $sd = 0.39$) was significantly slower than all others. Participants commented that the concave bend was harder to hit because of its narrow width, so the finger was stopped when the nail hit the surface. There was a slight advantage for the convex bend; on average, taps on the convex bend required the least time ($m = 0.61$, $sd = 0.12$). The mid area, even though it was considered very positive as a kind of rail that offers a convenient angle to tap on from above, did not provide a significant time advantage ($m = 0.64$, $sd = 0.13$). There was no difference between upper and lower flat portion indicating that the height of the structure did not have an impact on the results. In the RowTap task, an ANOVA did not show a significant effect of structure ($F_{1,318} = 3.64$). However, post-hoc pairwise comparisons revealed a longer task completion time for the concave bend for all comparisons ($m = 1.64$, $sd = 0.87$). Again, the convex bend was fastest and also showed a low spread of data ($m = 1.26$, $sd = 0.22$), while the flat portions caused slightly larger task completion times. For SlideTouch, an ANOVA did not show a significant effect of structure

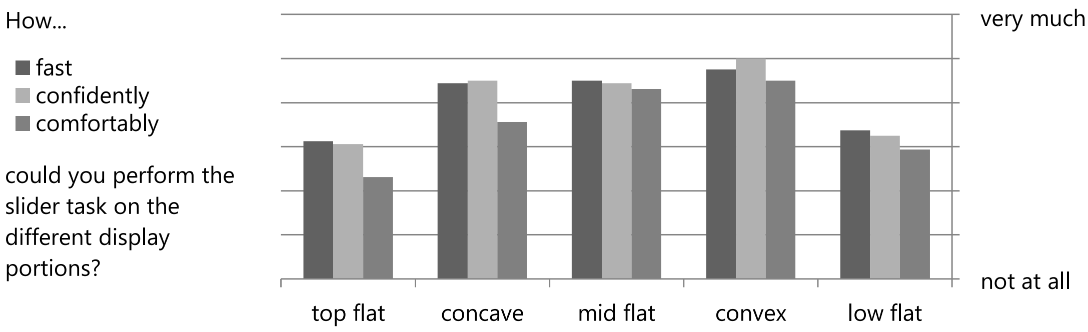

Figure 5.3: Subjective results for the slider task.

on the task completion time when adjusting the 5 different percentage values nor when just considering the 100% case where the longest distance had to be covered. The worst performance was achieved with the lowest flat screen portion ($m = 5.97$, $sd = 2.10$). Best results were achieved for the convex ($m = 4.54$, $sd = 1.37$) and the mid flat screen portion ($m = 4.58$, $sd = 1.59$).

Subjective feedback A Friedman's ANOVA revealed no significant effect of structure on the subjective measures speed, confidence and comfort for the button tasks. When asked about the potential for bends to improve usability, participants' ratings increased from a neutral to a positive rating from the first to the second run of tap tasks, indicating that users need to get used to this new kind of interface. Potential is estimated significantly higher for the slider task than for the button tasks (t = 4.74). For the SlideTouch task, there was a significant effect of structure ($X^2(4) = 5.02$). The ratings (see Figure 5.3) for the convex bend look promising, with the highest ratings regarding speed, confidence and comfort.

User experience Both measures of user experience, hedonic and pragmatic quality, were rated highly positive. Especially the latter was assessed as desired, with high agreements for the properties *simple*, *clearly structured* and *practical*.

5.2.3 Interpretation & Discussion

The results do not indicate that the two button tasks could benefit from the convex or concave structure in terms of subjective performance, so **H1** *(Pointing tasks can be performed with more confidence on structured display portions)* has to be rejected.

For the RowTap task, there were slight advantages of the convex structure regarding task completion time, but the differences were not significant, so **H3** *(RowTap can be performed faster on structured display portions)* also has to be rejected.

The effect of structure on perceived confidence was significant for the sliding task, so **H2** *(SlideTouch can be performed with more confidence on structured display portions)* is confirmed. There was no effect on task completion time; therefore, **H4** *(SlideTouch can be performed faster on structured display portions)* has to be rejected.

However, the positive subjective ratings and the trend to improve task performance when interacting on the convex shape indicate that this structure is helpful at least for linear sliding tasks.

Essence A user study showed that shaped surfaces can provide haptic guidance for interaction when the interface concept is designed appropriately such as in the sliding task. However, as the results of the concave bend show, surface shapes need to be developed carefully to not degrade performance.
Participants named various use cases where bends can be used to support the interaction. Adjusting continuous values such as temperature, volume, or zoom level, but also the spatial division of a large interactive area and the usage as a hand rest were considered promising.

5.3 Shape-enabled interaction: Bend interaction

In the last section, results showed that bends were better suited for the adjustment of continuous values than they were for tap interaction. This was because the user could not take advantage of the support through surface shapes as the haptic perception process was finished before an exploration could begin.

Since selection is a common task when performing menu interaction, the next section discusses a new approach of triggering. Haptic properties are used in combination with touch gestures; the movements on the surface allow to perceive its shape and integrate it in the interaction.

5.3.1 Enriching touch interaction with haptic barriers

Approach

BMW's *functional bookmarks* are physical buttons with a capacitive sensing layer on its surface, which allow to preview the functionality behind a hardware button before pressing it[51]. Hovering with a mouse cursor has a similar effect, while for touch interaction, there is no difference between selection and confirmation [41]. Touch gestures towards different directions have been shown to enable rich interaction [62]. However, they require a quick hand movement and still lack immediate haptic feedback to communicate if an action has been successfully performed. Structuring the interactive space, shaped surfaces can enhance this by providing something to perceive when the finger crosses a haptic barrier.

Use cases

A bend can be used to arrange items along it. Different elements can be aligned next to each other as it is done in task bars in common operating systems. As discussed before, buttons such

[51] `http://www.bmw.com/com/en/insights/technology/technology_guide/articles/functional_bookmarks.html` [cited 2013/12/01]

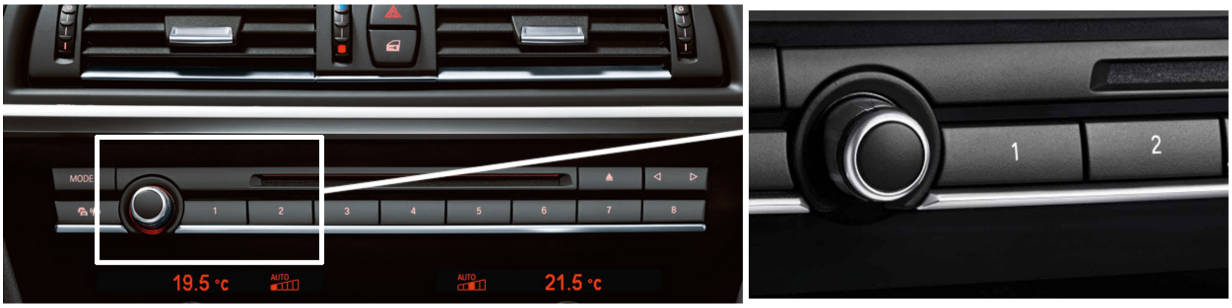

Figure 5.4: BMW functional bookmarks are realized as physical buttons in the center stack with free assignable functionality[52]. A rail provides haptic guidance.

as functional bookmarks are often aligned in a row, in this case even with an additional guiding rail as in Figure 5.4. Bends are therefore well suited to serve as a place to select functionality such as menu items or shortcuts.

5.3.2 Evaluation – Dragging in the vertical plane

Section 5.3.2 is based on: S. Rümelin, F. Brudy, and A. Butz. Up And Down And Along: How We Interact With Curvature. In *Workshop 'Displays Take New Shape: An Agenda for Interactive Surfaces' in conjunction with the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*, 2013 [240]. The prototype was implemented by Frederik Brudy in the course of an internship, under the supervision of Sonja Rümelin.

Concept and realization - Trigger points on bends

To resolve ambiguity of touch points on flat screens, Moscovich has proposed *Sliding Buttons* [191]. Those buttons do not need to be pushed but the touching finger has to slide across them in a certain direction. This concept aims to prevent unintentional selection when neighboring buttons' sliding directions are different. In contrast to flat surfaces, curvatures can be perceived haptically. Bends as in the prototype described in Section 5.2.2 have different sections that can be distinguished. For example, when dragging downwards from the top border of the overall screen, at a certain point the flat surface *begins* to bend. Then, there is the *peak* of the bend in the middle of the overall curvature, and the point where the curved section *ends* and passes into the flat surface again.

Combining those two concepts, the idea is to perform dragging gestures until a specific point of the haptic barrier, to activate different actions. Dragging farther than the end of the curvature could then trigger a different function than lifting the finger at the peak.

[52] © Photos BMW Group.

In this project, we wanted to investigate how accurately and how reliably across different users those different positions can be recognized when dragging in different directions. We used the previously described prototype to examine both convex and concave curvature.

Study

Participants 12 participants (6 female, 6 male) with a mean age of 25 took part in the evaluation. Due to confidentiality rules, all of them were working for the BMW Group. All of them used a smartphone or a tablet computer at least once a week and were used to touch interaction. All participants were right-handed.

Task The task was to perform dragging gestures from a given starting point which was indicated with a cross on the display. The required direction and end point for a gesture were given textually. When the correct position was reached, the finger was lifted off the surface and the selection was confirmed by pressing Enter on a keyboard.

Conditions On the two different bends, the target positions to end the dragging gesture were beginning, peak and end of the bend. The gesture was either performed upwards or downwards.

Study design The study used a within-subjects design. The order of the trials was counterbalanced, and performed twice by each participant.

Apparatus The prototype described in Section 5.2.2 was adjusted by switching from an FTIR to a DI recognition setup. With the FTIR setup, light accumulates in the bends. In the former study, recognition was optimized to either recognize touches on the flat or on the bent areas, while now the transition of gestures from the one area to the other was critical. Moreover, the diffuser foil was attached to the back of the acrylic plate using double-sided adhesive foil so that the surface to perform the touch gesture on was smoother and thus more comfortable. Moreover, it was closer to the appearance of a real screen. A Java application was developed for the graphical user interface and the gesture tracking.

Procedure Participants were asked to imagine sitting in the driver's position while interacting on a center stack display. After this introduction to the scenario, a familiarization phase followed where they could get used to the screen. Then, the first condition was started by displaying the first starting point. Participants were asked to touch it and then to look straight ahead where the current moving direction and the target point were indicated on a screen. They had to move their finger to the respective point, lift the finger and press Enter on a keyboard in front of them. In the second run, they were asked for their evaluation of different subjective measures. After both runs had been completed, a semi-structured interview was conducted to capture further feedback and ideas. Overall, the study took about 45 minutes.

Independent and dependent variables The independent variables were the *type of bend* (convex, concave), the *movement direction* (upwards, downwards) and the *target position* (beginning, peak, end). Objective dependent measures were task completion time and the trajectory of the touch gesture, while subjective feedback on each trial was assessed regarding unambiguousness, speed, ease of use and confidence of the interaction. Overall subjective questions were asked on further preferences.

Hypotheses

H1: The end of a curve can be identified faster than the beginning.
H2: The convex peak can be most accurately identified.
H3: The convex peak receives the best subjective ratings.
H4: Moving downward is more comfortable than moving downwards.

Results

Only the second run of trials was used for the analysis to reduce the effect of learning.

Task completion time There were no significant effects regarding task completion time.

Accuracy of target points Figure 5.5 visualizes the confirmed end points of the touch gestures. The maximum overshoot was significantly lower when performing a downward movement than when going upwards (t(71) = 8.64). The same applies for the final results (t(71) = 5.94). This indicates that the estimation of the bends' sections was easier when going from top to bottom. Moreover, an analysis of variance (ANOVA) revealed that when targeting the end of the curve, the overshoots were smaller than when targeting the beginning or the peak of the curve (F(1,142) = 1.70). Participants first explored the overall curve before going back, resulting in larger corrections when targeting the beginning of the curve.

Trajectories Looking at the trajectories of the touch gestures, we found a combined effect of movement direction and type of bend (F(1,140) = 41.95). The touching finger is deviating towards the left when moving upwards, while for downward movements, the finger deviates towards the right. This effect is larger for the upper bend than for the lower one. This can be explained with the hand-reach envelopes (see Section 2.1.2), which define the rotation area of the driver's arm: with an outstretched arm, areas in the middle of the center stack can be reached comfortably. For the vertical upward movement, this has to be compensated with a horizontal left movement.

Subjective ratings Subjective feedback was gathered through 7-item Likert scales. Pairwise comparisons with Bonferroni corrections showed that participants estimated it faster and easier to target the peak than either beginning or end of a curve. In addition, they felt more confident. Regarding the unambiguousness of the detection, the peak was also rated better than the other two positions ($X^2(2)$ = 15.33). Judging their own performance, there was a significant effect of the type of bend ($X^2(1)$ = 3.60) and the direction ($X^2(1)$ = 5.87), with a benefit of downward movements on the concave bend. 92% rated the downward movement as more comfortable, while 8% preferred an upward movement.

Interpretation

Target overshoots were smaller when targeting the end of the bend than beginning or peak. A movement across the whole bend seems to be necessary every time a specific section has to be identified to "understand" the bend, resulting in an increased correction movement when targeting the beginning. Still, this result was not significant, so **H1** *(The end of a curve can be identified*

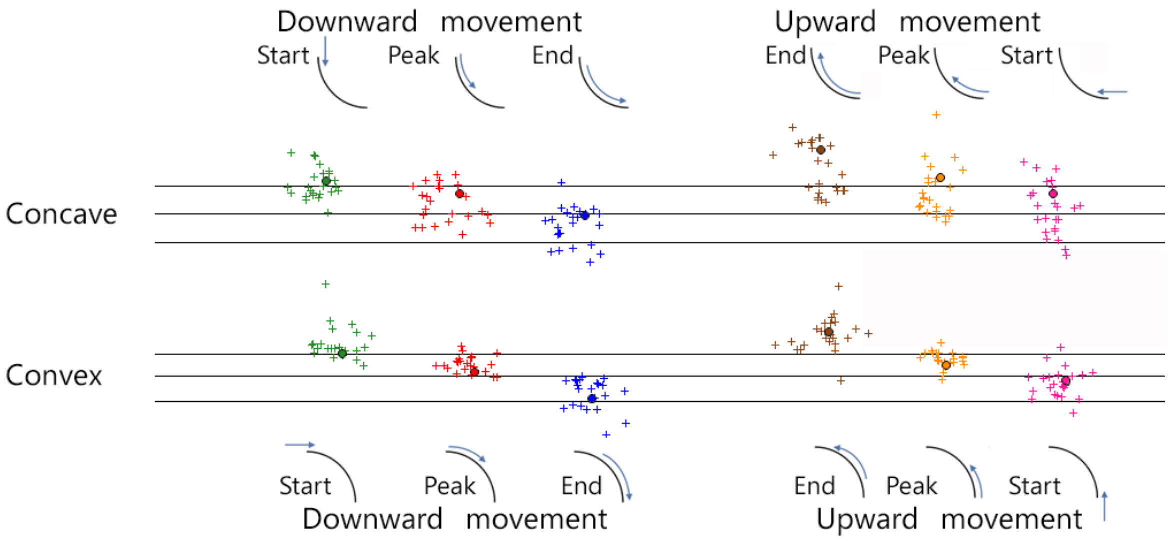

Figure 5.5: Point cloud of confirmed end points of touch gestures.

faster than the beginning) is rejected. The accuracy of recognition was not significantly influenced by the target position, therefore **H2** *(The convex peak can be most accurately identified)* is rejected, too. The subjective impression, however, indicates that dragging at the peak was considered superior in terms of unambiguousness and confidence while interacting as it sticks out prominently, so **H3** *(The convex peak receives the best subjective ratings)* is accepted. Moreover, **H4** *(Moving downward is more comfortable than moving downwards)* is confirmed. This confirms the results from Section 4.2, where an upward touch gesture on a flat screen was also considered to be uncomfortable. The direction of movement also had an influence on the amount of overshoot; dragging downward caused less additional movement.

Essence

Overall, there was no clear favorite combination of dragging direction, target position and orientation of the curve. However, the study results indicate that both peak and end of a curve have the potential to be identified consistently and can be integrated in the interaction with physical bends. Downward dragging is preferred to upward movements regarding comfort and accuracy.

5.3.3 Evaluation – *BendSelect*: Dragging in the horizontal plane

Section 5.3.3 is based on: S. Zimmermann, S. Rümelin, and A. Butz. I Feel it in my Fingers: Haptic Guidance on Touch Surfaces. In *Proceedings of the International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*, pages 9-12, New York, NY, USA, 2014. ACM Press [319]. The prototype was implemented by Simone Zimmermann in the course of an internship, under the supervision of Sonja Rümelin.

A common automotive interface is a remote rotary controller. It is placed ergonomically in the center console where the hand can rest on during the interaction. Touch-sensitive screens which are increasingly integrated into automotive cockpits are mainly placed vertically in the center stack, with the drawback that interaction without support is exhausting for the executing arm. Brüninghaus and Meier-Ahrendt [34] highlight the potential of touchpads to control the growing amount of functionality that is already available in the car. They are increasingly integrated (see Section 2.1.3) as they allow for different types of interaction while being placed at an ergonomic position. For this project, we therefore decided to investigate touch interaction at the position of today's controllers.

Concept and realization - Unimanual multifinger interaction

Most touch interfaces are static. The user has to approach the screen and touch it at the position a button is displayed. *Perkinput* [9] is a touch input system to write Braille characters blindly, where index, middle and ring finger of both hands represent the six points of a character. Tapping with both hands onto a touch surface, it is not required to hit the interactive surface exactly, but the software can conclude from the number and positions of touching fingers which character is intended. Similarly, buttons could approach the user's fingers as soon as those touch the screen. In a second step, a mechanism for selecting one of those functions is required. Esenther and Ryall [68] developed a technique for the interaction on touchscreens that uses multiple fingers for dragging and an additional tap for selection.

Combining those approaches with the results in Section 5.3.2, multifinger control can be enhanced with touch gestures and the support of static haptic structures (see Section 3.4.2). Dragging across a bend can trigger the function associated with the respective finger. The concept is based on a touchpad on which the right hand is comfortably placed. Functions are assigned to the fingertips of index, middle, ring and little finger as soon as they touch the touchpad. The surface is extended with a haptic bend; a function is selected by dragging the respective finger across the bend, while leaving the others on the surface.

We wanted to investigate whether dragging with the support of static haptics can be used to interact on a touchpad. We conducted a user study to investigate the effect of unimanual multifinger interaction on distraction and usability.

a

Positioning \ Selection	Double tap	Vertical drag
Flexible along continuous bend	***BendTap***	***BendDrag***
Fixed at dotted elevations	***FixTap***	***FixDrag***
Flexible on plain touchpad	***FlexTap***	-

Figure 5.6: a: Overview of the different test conditions b: With BendDrag, buttons are aligned flexibly under the finger tips along the bend; selection is performed by dragging the button across it.

Study

Participants 12 participants (4 female) with a mean age of 27 took part in the evaluation. All of them used touchscreens on a daily (92%) or at least weekly basis. Two left-handed persons took part in the study; they were able to control the device with their right hand. Overall, 6 participants had learned to play the piano or guitar.

Task The given task was to select functions that were announced by pre-recorded audio commands. Those functions could be favorite functions or the main functions of the currently selected domain, such as play/pause, skip backward, skip forward and shuffle for the media player. We decided for abstract functions represented by a rectangle, triangle, circle and star.

Conditions Two types of button positioning were included in the evaluation: buttons were either displayed at a fixed position or the positions were flexible and adjusted to the fingers' touch points. This was supported by two different types of static haptics. First, a continuous, edge-like sharp bend across the touchpad was added to the surface to provide the fingers with coarse orientation. Buttons appear under the four fingertips when those are placed close to the bend. As a second variant, 4 distinct elongated elevations were added to the surface, forming a broken line similar to the continuous bend. They provide fixed positions for the fingers. Both bends were not straight but slightly curved to better fit the natural line of the finger tips. The radius was determined based on preliminary surveys. Selection was performed either by double tapping of the respective finger, or by dragging the finger vertically down across the haptic bend. The function was selected when lifting the finger below the bend. We decided for a double tap instead of a single tap because it promised to be more robust.

Figure 5.6 depicts the combinations and the associated variants' names (BendTag, BendDrag, FixTap, FixDrag). In addition to the four interfaces featuring static haptic feedback, an interface without haptics was included. The combination of flexible button positioning and selection by double tap (FlexTap) aims to serve as a base line and to test the general necessity and convenience of a graspable structure.

Study design We conducted the study in a dual-task scenario. The primary task was to observe driving videos which were displayed on a screen in front of the participant. In order to increase visual and cognitive attention towards the driving scene, questions about incidents along the route were asked afterwards. A within-subjects design was applied. The order of the five different interfaces was randomized for each participant. For each interface, participants had to perform 16 selections in a randomized order with all symbols equally appearing four times.

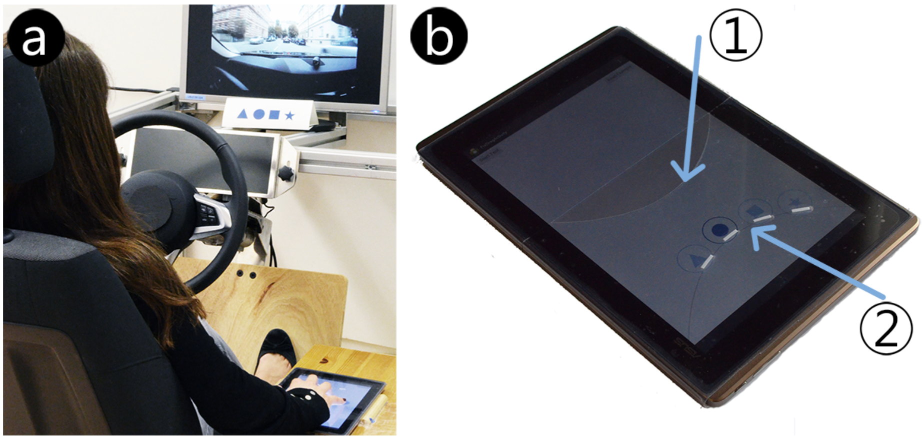

Figure 5.7: Study apparatus. a: Mockup with touchpad at the position of current remote controllers b: Different haptic structures attached to the tablet using silicon foil, forming a (1) continuous bend or (2) distinct elevations for each finger.

Apparatus A cut out silicon foil of about 0.6 mm thickness was applied to the cleaned surface of a 10.1" Asus Eee Pad running Android. The foil was self-adhesive due to the vacuum between it and the surface. In addition, the foil was fixed with tape on the back of the tablet to prevent from shifting. The tablet's capacitive multitouch sensing was still functional through the foil. Two different haptic bends were created: the cut out part of the foil formed the continuous, sharp bend. The second, dotted bend was smoother and formed by covering four slim rectangles of thick material with the foil. These elevations provide graspable portions on the surface and indicate the finger's intended positions.

The study was conducted in a mock-up equipped with a car seat as well as a steering wheel, but without pedals (Figure 5.7). The tablet was placed on a table on the right side next to the seat. To remind subjects of the mapping between fingers and functions, a printed sign showed the four functions in the area of a head-up display. Behind that, the screen for the driving videos was placed. All prototypes were realized on the same tablet using different areas, and based on the screen rotation feature of Android.

Procedure For every prototype, there was an introduction phase including an example run for all four fingers. Then, the driving video started and participants were asked to focus their attention towards the road scene. Automatically, symbols were announced and a success or failure sound was played as soon as the symbol was selected. The next symbol was given 3 seconds after a correct selection. The announced task was repeated immediately after a wrong selection. After each variant, participants filled out a questionniare to capture the respective subjective feedback. In the end, a semi-structured interview was conducted to obtain comparative feedback regarding different aspects of the interfaces. Overall, the study took about 60 minutes.

Independent and dependent variables We evaluated the five different *interfaces*. The dependent measures that were taken with the Android application were task completion time and errors. Moreover, glances towards the tablet, errors and other occurrences were observed and noted down by the researcher. After each run, questionnaires on the interaction [55], workload (NASA TLX [96]), perceived usability (SUS [32]) as well as the subjective rating of glances and errors were completed. Moreover, we collected subjective feedback regarding button positioning, selection modes, and the capability of each finger.

Hypotheses

H1: Flexible finger positioning requires less visual attention than fixed finger positioning.
H2: Flexible finger positioning allows for shorter interaction times than fixed finger positioning.
H3: Selection by dragging can be performed faster than double tapping.
H4: Static haptics support the user to feel more confident about the interaction than on a plain surface.

Results

The results are reported at a significance level of .05.

Task completion time An ANOVA showed that the interface had a significant influence on selection times ($F_{4,946}$ = 5.90). Pairwise comparisons revealed that interacting with BendDrag was significantly faster than with the other interfaces. Comparing the three different interfaces with the selection based on double tapping (BendTap, FixTap, FlexTap), there is no significant difference but a slight increase of task completion time the more structure that is provided. Dragging for selection was significantly faster than double tapping ($F_{1,757}$ = 15.97). There was no significant difference in the performance of the different fingers.

Errors Numbers of errors were not equally distributed, so a Friedman's ANOVA was used to evaluate the effect of the interface. There was a significant difference ($X^2(4) = 12.93$), with less errors for flexible button positioning. This is supported by the subjective estimation of errors ($X^2(4) = 10.56$).

Visual attention Visual distraction was measured as glances towards the touchpad. Overall, only few glances were observed, with the highest number for FixDrag (21 for all participants' 192 trials) and the lowest number for FlexTap (5). There was no significant effect on visual distraction. There was a tendency that flexible button positioning caused fewer glances than the fixed one.

Perceived usability and workload SUS and NASA TLX did not show significant effects. All interfaces showed a low to medium workload. FixDrag was rated worst (39 of 120 points), while FlexTap (24) and BendDrag (28) showed the best results. We found the same tendencies with the usability ratings.

Interaction vocabulary Since fixed button positioning was inferior in the previous categories, and for reasons of legibility, Figure 5.8 only depicts the ratings of the interaction vocabulary for the remaining interfaces based on flexible button positioning. The two interfaces based on the continuous bend (BendTap, BendDrag) were rated better regarding spatial proximity. They were also considered to be more directed, while FlexTap tended to be perceived as more incidental. The combinations FlexTap and BendDrag were said to be more instant and undemanding.

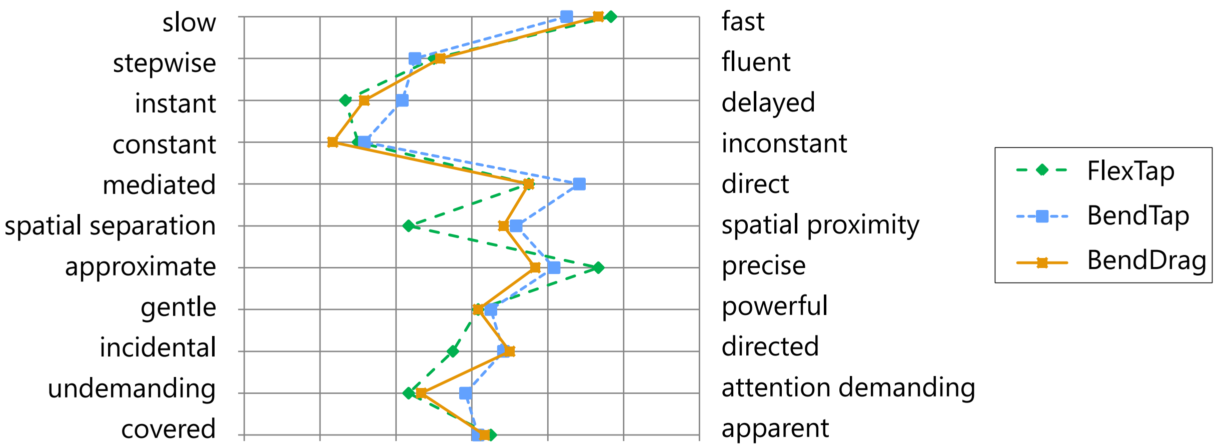

Figure 5.8: Overview of the ratings of the interaction vocabulary.[53]

Subjective feedback The interviews with the participants revealed the reasoning for the subjective ratings. The interaction without a bend allows to freely assign the screen space and therefore there are no restrictions on how to place the hand. However, the plain surface lacks tactile feedback. In contrast, when the bend was apparent, it restricted how one could position the hand. This was only a minor issue with the continuous bend, while it was commented to provide the user with confidence that the fingers were placed correctly. Although this was not necessary for the tap interaction, it was perceived as a guidance and "better with than without". Regarding the type of selection, double tapping was said to be more exhaustive than a single tap would have been; however, this was also positively highlighted as it allows for a good error tolerance. Unexpectedly, the tapping noise was mentioned to influence the product character negatively. On the other side, dragging was rated to cause less hand movement since the fingers do not need to be lifted, and to be ergonomic as the gesture was similar to making a fist. However, a contradictory opinion was that the dragging gesture was difficult to perform. Moving only a single finger while the others rest on the surface was said to be an unfamiliar motion sequence that would require some training, which made it exhausting after some trials.

Suitability of different fingers Flexible positioning along the continuous bend fit for all sizes of hands, while the dotted bend was less comfortable for larger hands of more than 25 cm span width. Subjective ratings for index and middle finger were better than for ring and little finger ($X^2(3) = 17.93$). Playing an instrument did not affect the results. Participants commented that using the whole hand for interaction by placing all fingers on the touchpad was unfamiliar but less exhausting than only using a single finger.

Interpretation

We observed less glances towards the touchpad with the flexible positioning; however, the results are not significant, so **H1** *(Flexible finger positioning requires less visual attention than fixed*

[53] Items were used in German, taken from [55]. Translations are taken from a later English version [56], which did not include the undemanding/attention demanding item any more; this is translated by the author.

finger positioning) is rejected. There was no effect of the type of positioning on task completion times, but just a tendency for faster interaction when positioning is less restricted, so **H2** *(Flexible finger positioning allows for shorter interaction times than fixed finger positioning)* is rejected, too. **H3** *(Selection by dragging can be performed faster than double tapping)* is accepted as dragging allowed for significantly shorter task completion times than selection through double tapping. **H4** *(Static haptics support to feel more confident about the interaction than a plain surface)* is rejected as the respective ratings did not reveal significant differences.

The selection methods evoked mixed opinions. Some participants rated dragging as convenient, since sliding over the surface is easier than lifting the fingers. However, it was said to be unfamiliar compared to double tapping. The latter was perceived as equally fast and exhausting. Opinions differed regarding the ergonomic properties of dragging. On the one hand, it was considered as positive as it only requires a short touch gesture; on the other hand, for some participants it was difficult to move the respective finger without affecting the others. This was not influenced by prior experiences with musical instruments.

Flexible positioning offered more freedom, no ergonomic constraints, and fit for all sizes of hands. Participants liked that they could determine the positions for interaction themselves. Interaction along the continuous bend restricted the interaction slightly but offered discernibility of the surface and haptic guidance. Thereby, it created a defined interaction area. Participants liked to be confirmed that their fingers were positioned correctly for the following interaction, even if this was not necessary when tapping for selection.

Essence

A low fidelity prototyping method was used to enhance an Android tablet with static haptic structures using silicon foil, and allowed us to quickly get into the evaluation phase.
The user study showed that dragging across a haptic barrier can serve as an alternative for double tapping and can be performed fast. In combination with the static haptic support of the continuous sharp bend, it can be used to enhance interaction on touch-sensitive surfaces with haptic perception.

5.3.4 Discussion

The previous two sections have investigated the use of horizontal bends integrated either in a vertical or horizontal interactive surface. Section 5.3.2 has described a user study on how well users can discriminate different portions of convex and concave bends. The beginning of a bend did not prove to be well suited for triggering an action. In contrast, peak and end could be unambiguously identified in terms of subjective and objective measures. We followed up with those results, comparing the selection by either dragging across a bend or double tapping in Section 5.3.3. Static haptics in combination with touch gestures such as dragging can serve as an alternative to direct touch interaction. The process of haptic perception requires the exploration of the surface, but can still enable fast interaction, and the results imply that the user's sense of confidence towards the interaction can be strengthened.

5.4 Shape-enabled interaction: Hollow interaction

Section 5.4 is based on: S. Rümelin and V. Lerch. Enhancing Flat Interactive Surfaces With Hollows: Prototyping And Interaction Approaches. *Presented as a Work-in-Progress demo in conjunction with the International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*, 2014 [244]. The prototype was implemented by Verena Lerch in the course of her master thesis [168], under the supervision of Sonja Rümelin.

Apart from bends, there is a variety of possible geometries a surface can take (see Section 3.4.) Surface shape should be chosen with regard to the intended functionality, as it is done with traditional physical control elements [90]. Functionality is assigned permanently and indicated by labels on the control. Keyboard concepts such as the "Optimus Popularis"[54] or the "Razor Blade Pro"[55] which use separate displays for each key allow to change the layout from one language to another or assign keys with specific functionality depending on the currently used application. However, due to a challenging manufacturing process, those approaches have not become widely accepted yet.

The goal is to support a flexible interface, but at the same time to allow for rich haptic feedback. An inherent property of interactive surfaces is that they can display changing content. With a shaped surface structure, they can provide points of reference and fulfill the requirements of *surface haptics* which physical handles offer through their constructive form (see Section 3.4.2). With appropriate interaction concepts such as the combination with touch gestures introduced in the previous section, *control element haptics* might be compensated for, too.

5.4.1 Supporting menu structures by haptic elements

Approach

Following the approach of Schmid et al. [254], we did not start this project with the definition of the functionality to be controlled, but first focused on exploring a broad range of shapes. This served to collect early experiences with different properties and allowed us to identify potentially useful characteristics.

Figure 5.9a depicts the set of shapes we created with modeling material and acrylic glass[56]. There were different types and sizes of bends, hollows and rotary-controller-like shapes. Based on those, we conducted an expert workshop with seven participants of either a technical, design or psychological background. In a first step, participants were instructed to put themselves in a driver situation while sitting in front of a curtain, behind which the differently shaped objects were placed. Bends were put up alternately in vertical and horizontal orientation. Then, participants were asked to explore the objects blindly (see Figure 5.9b) and think of ways how to

[54] `http://www.artlebedev.com/everything/optimus/popularis/` [cited 2014-01-20]

[55] `http://www.razerzone.com/gaming-systems/razer-blade-pro` [cited 2014-01-20]

[56] For more details on the prototyping methods, please refer to [244].

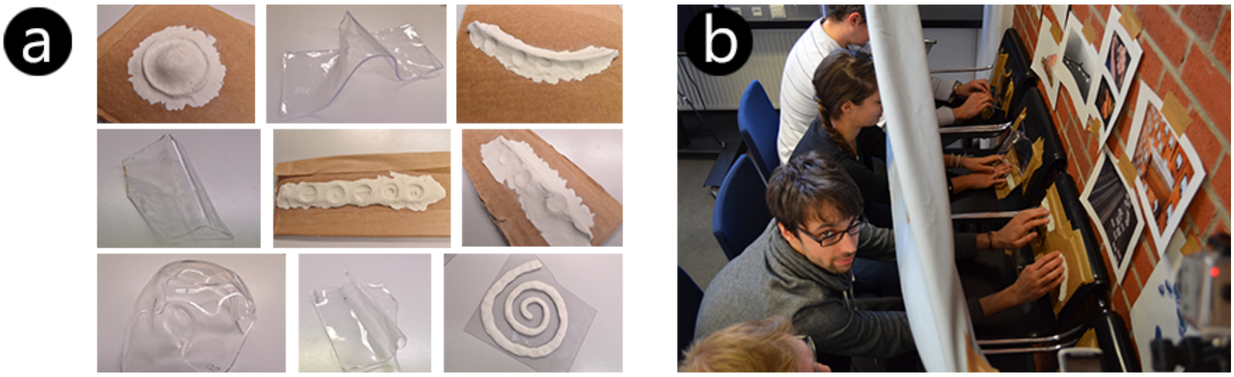

Figure 5.9: Preliminary shape exploration. a: A diverse set of shapes was created with modeling material and acrylic glass b: Participants of the workshop first explored the objects blindly.

interact with them. This interaction with the objects was video-taped for later analysis. In a second step, we revealed the objects and let participants discuss on their experiences.

We analyzed the videos with regard to macro- and micromotions that were used to examine the objects and to interact with them. Loomis and Lederman distinguish between exploratory and pursuit motions. The first are "rapid and continuous and (...) involve minimal use of tactile information" [172], while the latter are used to feel for details. Thereby, "hands (...) pause when the fingers reach critical points in the object contours, such as corners and linear intersections" [172]. This is exactly what we observed: most of the time, the exploration started with a vertical downward scanning motion to get a general idea about the current shape. This made it easy to detect the horizontal bends as they interrupted this movement. After this rough exploration, participants performed smaller movements on the object's surface to scan for more details. This movement stopped when a finger reached an irregularity. Then, further thorough sensing was performed. Those pursuit motions were more extensive for horizontal bends (see Figure 5.10) than they were for vertical ones, where participants often used their whole hand to grasp the overall shape to not slip down. This seemed to make it harder to explore small surface shapes. Hollows appeared to be the most interesting shapes. Most pursuit motions were spent to drag fingers across, into and out of the hollows in different linear directions or to tap into them. Circular touch gestures were performed along the hollows' borders. Most of the time, index fingers or other individual fingers were used for these activities.

In the discussions on the experiences of the exploration, hollows were commented to "afford to drag in and out" and that they "can serve as a reference point for further interaction". Shapes such as the horizontal bend or the triangular rail where one could hang on to and put weight on, were highlighted positively. The large circular objects were said to be limited in the number of ways how to interact with them, as only dragging around in different directions seemed meaningful. Lifting the curtain, participants were surprise how small the objects were. When manually exploring them, details had appeared larger. The comments confirm our observations on the bends; horizontal bends were said to be more convenient as they provide support and allow to put down the hand onto it.

Figure 5.10: Screenshots of video observations when interacting along a horizontal bend.

Use cases

Based on the results of the workshop, we decided to stick to the horizontal bends of the prototype that was used in the previous sections. Moreover, hollows had received positive feedback regarding their haptic unambiguousness and the possibilities of interaction, and are thus integrated into the prototype.

5.4.2 Evaluation – *HollowSelect*: Item selection

Concept and realization - Hollows for selection

A common task in an infotainment system is to select functionality. However, even a simple selection task is difficult to perform on a flat touchscreen while driving (see Section 3.2.3): the screen element has to be localized, then the finger has to be positioned, and finally, the finger needs to touch the screen at the exact position. Hollows create defined interactive areas that can be used to confirm the initial contact with the screen. Moreover, they indicate the area where an interaction such as a selection can be performed. However, hollows are not suitable to be integrated anywhere in a screen. In a map application where continuous graphical content is displayed, a large flat surface portion is preferred to one that is interrupted by physical features. Furthermore, there is a trade-off between the optimal screen orientation for mainly visual or manual interaction: visual content should be displayed vertically, while manual interaction should be supported by a horizontal orientation. Therefore, we decided to integrate hollows in the section between convex and concave bend of the former prototype. The medium part is now used as an administrative area, while the upper vertical part serves as the main display area.

Different concepts for the selection with and along hollows are evaluated. First, *TAP* is the common way to select an item in most today's touch-sensitive devices. The user needs to simply touch the respective element which is now displayed inside a hollow. *RIGHT_TAP* is derived from the usage of a mouse. Hovering is substituted with positioning the finger on the element, while the process of clicking for selection is substituted by touching the screen with a second finger. The first finger is supported by the hollow during the interaction. Touch gestures are used in the remaining concepts *DRAG_IN* and *DRAG_OUT*: the user has to either drag the finger downwards into a hollow or from inside the hollow downwards out of it to select the displayed item. The downward dragging direction of the last two concepts was chosen based on the results in Section 5.3.2.

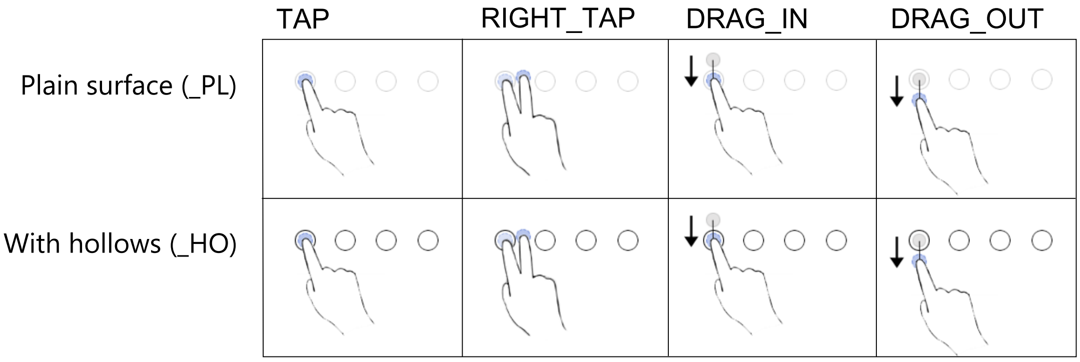

Figure 5.11: Four different selection concepts on two different surfaces.

Study setup

Participants 20 participants (6 female, 14 male) with a mean age of 28 took part in the evaluation. All of them were working for the BMW Group, but were not involved in the current research. 18 were right-handed; both left-handed people stated that they were used to control functionality in the center stack with their right hand. All of them interacted with touch-sensitive devices daily. Only one person had experiences with built-in touchscreens in cars. However, most participants had experiences with touch interaction on devices such as smartphones or PNDs while driving.

Task The task was to select one out of four menu items (*Music*, *Telephone*, *Navigation*, *Settings*) following the announcement of pre-recorded audio commands.

Conditions We evaluated the four different selection approaches described above on two different surfaces (see Figure 5.11). We used either a plain flat screen, or one that was enhanced with four hollows for the respective menu items. In addition, we included a version of extended hollows for additional questions.

Study design The study was conducted in a dual-task scenario. First, participants had to perform a car-following task in a driving simulator environment. The scenario was a multi-lane road where the driver had to stay in a constant distance of 75 m at a speed of 100 km/h. We used a within-subjects design. The order of the different conditions, including the four selection modes and a baseline run where participants were performing the car-following task without any additional interaction, was counterbalanced using a Latin Square. The order of the types of surfaces was changed during the runs, so participants alternately started with the flat or the hollow surface.

Apparatus We reworked the prototype we had used before. We cut the curved surface between convex and concave bend to be able to insert different plates into the section between them (see Figure 5.12). This way, we could compare the different surfaces at the same position and with the same conditions for image quality and touch recognition. A further refinement was the introduction of a mirror for the projection to decrease the overall depth of the prototype. We created the hollows by milling into the acrylic glass. Referring to the expert interviews (see Section 5.1) and some informal preliminary tests for size preference, we chose a diameter of 20 mm

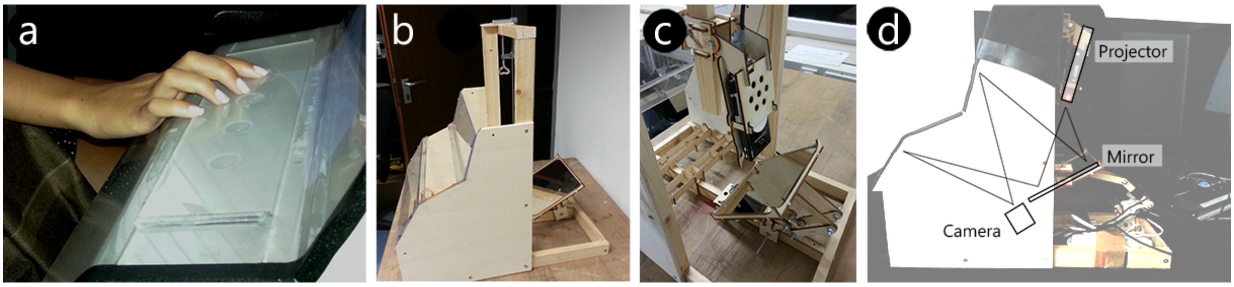

Figure 5.12: Prototype including bends and hollows. a: Final prototype b: Between the bends, there is a gap for exchangeable plates c: Back view with projector and mirror d: Setup of the different components.

for the hollows, about the double width of a standard finger tip. Furthermore, we built a set of plates containing hollows with "children": a smaller hollow overlaps with the larger one to create a support when dragging in or out. As the diffuser layer, we used rear projection paint (white Screen Goo) which we applied to the flat backside of the acrylic glass plates.

The graphical user interface as well as the tracking of the interaction was realized in a Java application. The driving scene was displayed on a 56" screen (Philips Cinema 16:9). The mock-up consisted of a seat as well as a steering wheel and pedals (Logitech MOMO Racing) to control the car in the simulation.

Procedure At the beginning of the study, the mock-up's seat and arm rest were adjusted to fit the participants' general ergonomic needs. After the introduction of the first interface, participants were asked to perform at least four successful selections. Then, they started driving, and as soon as speed, longitudinal and lateral position were reached, they performed four further selections before the trials were recorded. 16 menu items were selected with each system. They were announced after random durations of 5-8 seconds. After each selection, acoustic feedback was provided. When the wrong item was selected, the item was announced again immediately. After each trial, the driving simulation was stopped, and the participants answered questionnaires regarding the system they had just tested. Selection modes were tested in blocks; after each block, questions comparing the influence of the different surfaces were asked. In the case of DRAG_IN and DRAG_OUT, an additional comparison with the respective children plate was performed. In the end, a semi-structured interview was conducted to gather further subjective feedback. All the time, the researcher was present to observe task executing and to take notes of unexpected behavior. Overall, the study took about 90 minutes.

Independent and dependent variables The independent variables in this study were the *selection approach* with four levels, and the *surface type* with two levels (see Figure 5.11). Additionally, we asked participants to compare the plain and hollow surface to a surface with extended hollows. We measured task completion time and errors, as well as driving behavior with regard to lateral and longitudinal deviation from the ideal position. Furthermore, we collected subjective feedback on user experience (AttrakDiff [99]), subjective workload (NASA TLX [96]) and asked further questions on confidence, distraction and glance behavior.

Hypotheses

- **H1:** Hollow-supported interaction improves driving behavior compared to interaction on a flat surface.
- **H2:** Hollow-supported interaction is less visually demanding than the interaction on a flat surface.
- **H3:** Hollow-supported interaction results in less errors than the interaction on a flat surface.
- **H4:** Hollow-supported interaction increases the subjective task performance compared to interaction on a flat surface.

Results

Results are reported at a significance level of .05.

Driving behavior The data sets of two participants had to be excluded from the analysis due to erroneous files. Driving behavior is defined by the measurement of lateral position (how well could the participant stay in the center of the lane) and longitudinal position (how well could the distance to the front car be maintained). To eliminate the effect of individual driving performance on the results, the difference between the measurements of a test drive and the baseline drive was taken for the analysis.

The ideal longitudinal distance was instructed to be 75 m. Within the baseline drives, the mean distance was slightly higher with 81.12 m, while the mean overall distance during the drives with an additional task was between 88.22 (DRAG_IN_PL) and 98.50 (DRAG_OUT_HO). An ANOVA did not show a significant effect of neither type of surface ($F(1,142) = 0.74$) nor selection ($F(3,140) = 1.19$) on the amount of deviation from the baseline drive. Since TAP_PL represents the traditional way of touchscreen interaction, we also compared the mean deviation values with regard to the TAP_PL drive. Again, we did not find significant effects.

The deviation from the lane's center was also analyzed as the deviation from the baseline drive. Again, neither the type of selection ($F(3,140) = 1.28$) nor the screen surface ($F(1,142) = 0.01$) had a significant influence on the driving behavior.

Task completion time There was a significant effect of the type of selection on task completion time ($F(3,156) = 10.82$). TAP ($m = 1.90$, $sd = 0.77$) was performed significantly faster than all other means for selection. RIGHT_TAP was significantly slower than all others ($m = 2.47$, $sd = 9.69$). Using either the plain or shaped surface did not have a significant effect on the results.

Errors The overall number of errors was low for all combinations of selection approaches and surface types. Most errors appeared when using TAP_HO, where 10 out of 320 trials led to a wrongly selected menu item. The surface type had a significant effect on the number of errors ($F(1,156) = 5.69$); participants more often selected a wrong item on the surface that included the engraved hollows.

User experience All variants were rated to be neutral to self-/task-oriented with regard to their hedonic and pragmatic quality. Figure 5.13 shows the different ratings grouped by the selection mode. There was a significant effect of the respective selection approach ($F(1,152) = 7.58$);

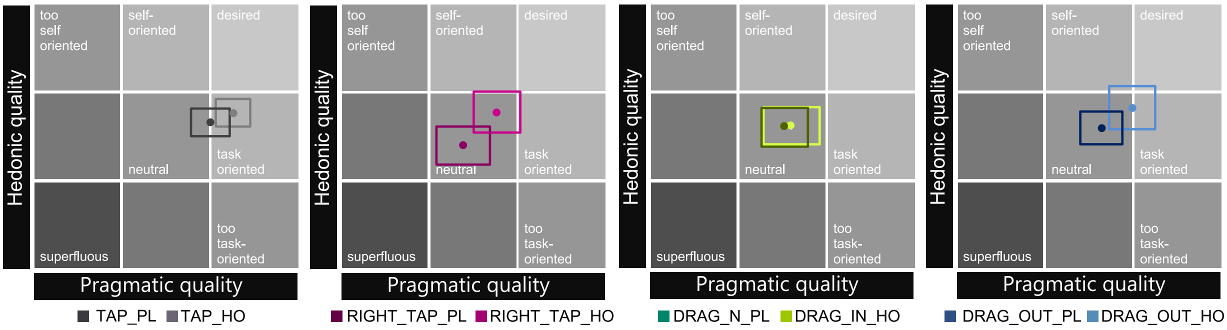

Figure 5.13: Results of the AttrakDiff for the different variants of *HollowSelect*.

TAP was rated best regarding pragmatic quality. Moreover, there was a significantly better rating regarding both pragmatic (F(1,152) = 8.11) and hedonic (F(1,152) = 6.14) quality for the variants that integrated hollows.

Subjective ratings There was a significant effect of the selection mode on the subjective workload estimation captured with the NASA TLX ($X^2(3) = 14.67$), with pairwise comparisons revealing that TAP is perceived as less demanding than RIGHT_TAP and DRAG_OUT. Moreover, the analysis revealed that interacting on the plain surface was regarded as more demanding than on the surface with hollows ($X^2(1) = 3.20$).

We asked further questions on the perceived distraction from the driving task, focus on the road, visual distraction, and confidence in the non-primary interaction which were answered on 7-item Likert scales. Participants felt less distracted when interacting on the hollow-enhanced surface ($X^2(1) = 8.00$). Moreover, pairwise comparisons revealed that TAP caused a lower perceived distraction than RIGHT_TAP and DRAG_IN ($X^2(3) = 18.48$). Participants stated more often that they had the feeling to not fully concentrate on the road scene when interacting on the plain surface ($X^2(1) = 7.12$). This is confirmed by the subjective estimations of visual distraction off the road; the plain surface seemed to require more glances towards the interactive surface ($X^2(1) = 11.84$). In addition, participants were more confident in choosing the correct menu item when interacting on the non-planar surface ($X^2(1) = 4.00$).

Preference When asked which combination of selection and surface they would prefer while driving, 75% of the participants named one that included hollows. Figure 5.14 depicts the distribution; the only selection mode on a plain surface that was chosen was TAP_PL.

Hollows with children, which were presented after testing the selection modes DRAG_IN and DRAG_OUT in the driving part of the study, were said to support the interaction. Half of the participants who prefer hollows for those selection modes would chose the additional support for the dragging gesture.

Interpretation

The analysis of driving data did not reveal a significant effect of one of the variants. Regarding longitudinal and lateral deviation, there was a large spread of data and no differences regarding the mean values, so **H1** (*Hollow-supported interaction improves driving behavior compared to*

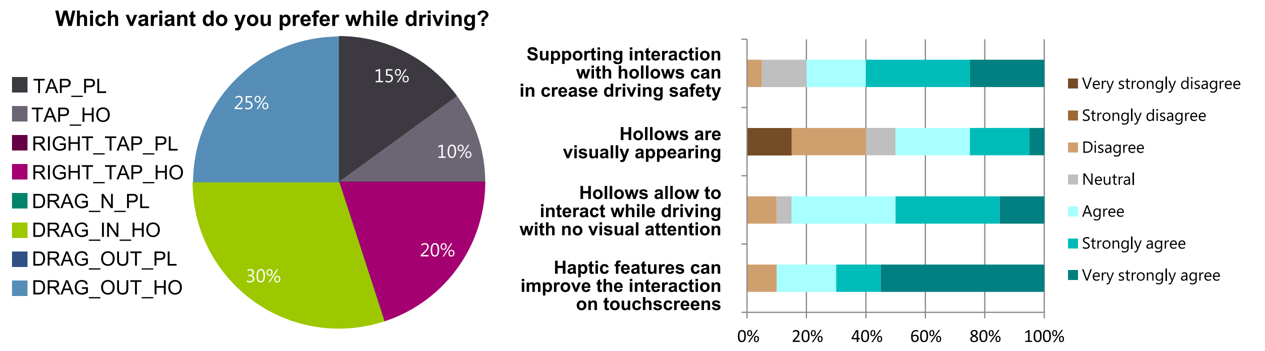

Figure 5.14: Preferences and subjective ratings for the different variants of *HollowSelect*.

interaction on a flat surface) is rejected. However, from the subjective ratings, we found that participants felt less distracted from the driving task and that they could better concentrate on the road scene when interacting on the surface equipped with hollows.

We did not objectively measure the glance behavior during the studies. However, we collected the subjective impression on how visually distracting the interaction with the different variants was perceived. The analysis revealed a significantly better rating for the shaped surface than for the plain one. Moreover, in the post-study interviews, 85% agreed that hollows in interactive surfaces can allow blind interaction (see Figure 5.14). Therefore, we found indicators for **H2** (*Hollow-supported interaction is less visually demanding than the interaction on a flat surface*), but have to reject it as this was not objectively verified in this study.

Contrary to our expectations, the results show that there were significantly less wrong selections on the plain surface, so **H3** (*Hollow-supported interaction results in less errors than the interaction on a flat surface*) is rejected. Participants were able to use their visual and haptic sense to search for the item to be selected, and they made use of this by scanning with their fingers over the surface. In this process, they sometimes selected a wrong item incidentally. When they got an audible notification of the error, they could scan further and continue to select the correct one. This ability for error recovery was valued in the subjective rating of confidence to select the correct item. This was significantly higher for the shaped surface than it was for the plain one.

H4 (*Hollow-supported interaction increases the subjective task performance compared to interaction on a flat surface*) is accepted since the analysis revealed a significant effect for the benefit of the surface with hollows regarding the AttrakDiff ratings and the additional questions on distraction, focus on the road scene and visual attention. Moreover, the concluding preference ratings were answered in favor of the hollow variants.

RIGHT_TAP, DRAG_IN and DRAG_OUT were specially designed for the interaction with the non-planar surface, and therefore benefit in particular from the hollows. TAP is the common selection mode on established flat touchscreens, and hollows do not support its search phase since there is no pre-selection contact with the screen (see Section 5.2.1). However, the results of TAP_HO were consistently better than those for TAP_PL regarding the subjective measures. When asked for their favored surface after the driving test, 75% of the participants preferred the surface with hollows to the plain surface. General arguments in favor of hollows that emerged from the post-study interviews (frequency of occurrence is given in brackets) are that interactive elements that are associated can be found quicker (7) since the surface provides spatial orientation points (7). Moreover, the overall concept allows for blind interaction (5) and the surface shapes provide feedback for the interacting finger (5). In addition, participants commented that placing a finger in a hollow "feels right" as it fits well in there (4). Drawbacks were seen in the restrictions which hollows pose for the flexibility of the touchscreen, which is even worse for hollows with children (5). Furthermore, the specifically designed interactions were unfamiliar and therefore not intuitive to perform (4). Observations revealed that RIGHT_TAP, which involved the coordination of two fingers, was too complex. There was no positive effect of the dragging gestures on the results compared to the TAP selection but single results that the exploration during the gestures can increase the distraction. This was explained by the novelty of the concepts, and regarding most measures there was no significant decline in performance. Overall, the preferences were equally distributed over the different selection approaches (see Figure 5.14).

Minimal visual attention is required for the interaction while driving, but there are situations where visual attention can be directed towards the surface, for instance when stationary. DRAG_IN was designed in a way that as soon as there was a touch event inside a hollow, the respective item was selected. Redesigning this to make use of the event that is triggered only when the finger is lifted off the screen, DRAG_IN can be combined with TAP. The mere contact does not cause a selection and an exploration is possible if wanted, but at the same time, a quick and familiar interaction is possible. Depending on the current context, the hollow can then serve to support the interaction (DRAG_IN), but does not disturb a shortened direct interaction (TAP).

Essence

> In this project, we combined two horizontal bends with engraved hollows to provide haptic orientation points and support selection tasks. Hollows are placed between the two bends. The user can first position the hand along the rough structure and then start to explore the screen's surface features.
> We conducted a user study to evaluate different selection approaches including tapping with one or two fingers and dragging gestures. There was no significant effect on driving performance, but participants' subjective opinion was that interacting with the shaped surface can significantly increase the attention towards the road scene. This holds true even for simple tapping interaction where the haptic features of the hollow do not support the selection but only confirm the interaction.

5.4.3 Evaluation – *HollowWidgets*: System integration

Concept and realization

The last section has introduced our first experiences with shaped surfaces that integrate hollows to ease spatial orientation and provide feedback for touch interaction. As a next step, we wanted to see how hollows can integrate more functionality and further investigate the behavior and experiences with hollows.

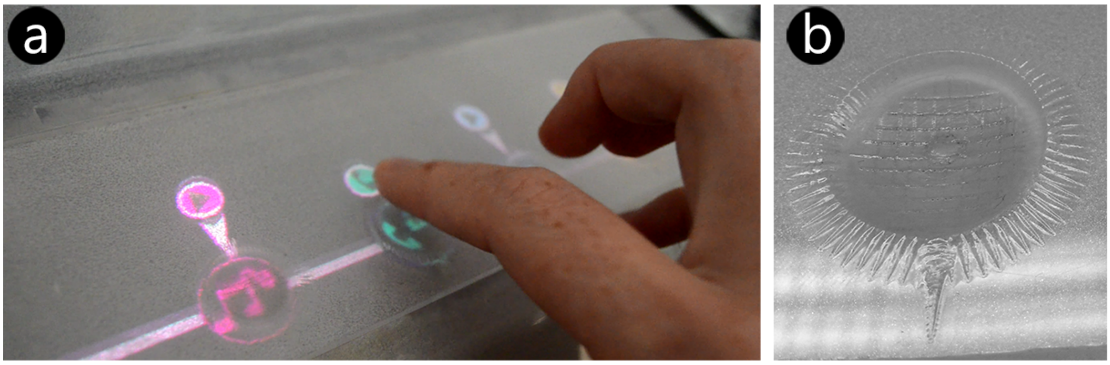

Figure 5.15: a: The *HollowWidgets* concept assigns pieces of functionality to the different hollows and provides a basic set of possible interactions to control it. b: Detailed view of a hollow with coarse-grained texture, notches along the border and a conical engraving to support the localization.

Most frequently used functions vary from user to user, so the idea is to provide a flexible, yet haptically supported interface. *Widgets* are commonly used on smartphones or desktop computers to provide an overview of information such as the weather forecast or currently played music. They also provide some basic functionality to adjust the displayed information. We decided to assign such widgets to the hollows; static haptics support the permanently available functionality. Compared to (1) fixed hardware buttons, (2) concepts like *functional bookmarks* and (3) flat touchscreen, the integration into the shaped display offers different advantages. It allows to (1) initially chose the individual favorite widgets and adjust them later on, (2) display information at the position the control is located and (3) it provides perceivable haptic features. Moreover, the hollows themselves afford different types of interaction, which can be assigned to the functionality which the *HollowWidgets* provide.

Regarding the functionality, we chose some basic "high frequency functions" [97] from which a user can select; in our example, those are *music*, *navigation*, *phone* and *ventilation*. Each widget is assigned a basic functionality and particular associated content, for example playing a preselected radio station, starting the navigation towards a specific target location, calling a favorite contact or switching on the ventilation. The details can be adjusted if required. Moreover, when a widget is activated, one can adjust continuous values such as volume or ventilation strength. A widget can also be deactivated.

Those actions are mapped to different touch gestures as depicted in Figure 5.16. From a main menu, there is a sub-view in which the user can choose from a list of functions and drag a particular entry at a hollow to place the respective widget there (DRAG_AT). Similarly, a settings icon can be dragged onto each hollow to adjust the associated functionality. To activate or deactivate a widget, DRAG_IN and DRAG_OUT actions are chosen. This is visualized as an icon such as a play button that slides into the hollow. A rotating gesture along the border of the hollow is used to adjust continuous values (ROTATE). The engravings around the border of the hollow together with visual highlights serve as a signifier for this action. We decided not to assign a specific action to a simple tap gesture as we planned to investigate full blind interaction which is not possible with tapping. However, as discussed in the last section, the DRAG_IN gesture is

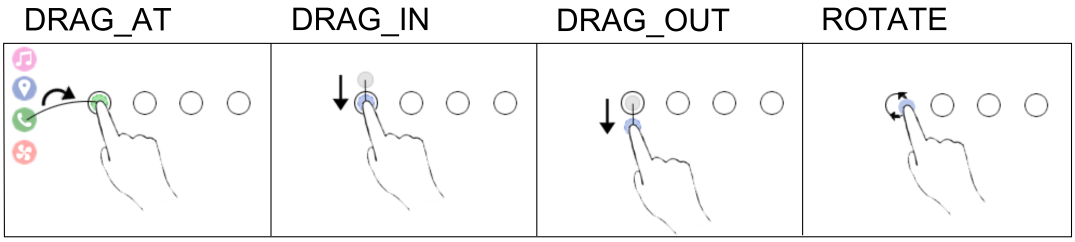

Figure 5.16: Possible actions in the *HollowWidgets* concept. Details can be found in the text.

implemented to be triggered when the finger is lifted off the screen, so it can be substituted by a simple tap.

The goal of the study was to evaluate the HollowWidgets concept and how well it can be performed as a secondary interaction, so we decided for an exploratory study. From the feedback of the previous study and the lack of significance in the driving data, we chose a more complex driving task than the car-following task we had used before.

Study setup

Participants 12 participants took part in the evaluation (2 female, 10 male). Their mean age was 29, and all except one were right-handed. The left-handed person indicated that interacting on the center stack with the right hand was familiar. All of them were used to touch interaction, but 66% had not used an integrated touchscreen in the car before.

Task First, participants were instructed to personalize the order of the menu items using the DRAG_AT gesture. During the first two drives, the task was to interact with the basic HollowWidgets interactions, DRAG_IN, ROTATE and DRAG_OUT. For the third task, the participants were asked to drag the settings icon onto one of the widgets (DRAG_AT), adjust the functionality by selecting the respective entry in the settings menu via ROTATE and DRAG_IN gesture, and perform the basic tasks again.

Study design The study was conducted in a dual task scenario. The primary task was to drive with a constant speed of 80 km/h on the center lane of a three-lane motorway. A second car was following on the left lane and the task was to keep this one in the left side mirror. Therefore, it was required to constantly observe both speed indicator and mirror. The order of the first two drives was alternated. One time, participants were allowed to look at the screen when they felt it was necessary (LOOK). The other time, they were asked not to avert their visual attention off the road scene (BLIND). In the third drive, glances were allowed to execute the tasks.

Apparatus The study was conducted in a driving simulator environment. The prototype was further adjusted. From the previous study, we learned that participants who tried to interact without any visual attention towards the screen wished to be able to distinguish the individual hollows. This is in accordance with research on traditional physical controls (see Section 3.4.2), where it is important to provide distinguishable haptic impressions for different functionality. Therefore, we created different textures in and around the hollows (see Figure 5.15b). We used engravings to make the hollows either feel smooth or coarse-grained and added a Braille-like bulge in one hollow. Moreover, we added notches to the border of the hollows to support 1) dragging gestures into or out of the hollow by providing kind of a rail, and 2) rotational gestures by providing a different sensation the quicker a rotational gesture is performed. An additional conical engraving was added to connect the hollows to the lower convex bend, where we observed that users tended to start positioning their hand. Auditory feedback was provided to support the circular dragging (click sound) and when an icon was dragged in or out (confirmation sound).

Procedure At the beginning, participants were introduced to the prototype and its touch functionality, as well as the concept of widgets associated with the hollows. The different possible interactions were demonstrated. Then, a first questionnaire was answered on the potential of the system. After that, participants configured the system by distributing the basic functionality among the hollows. Thereby, we wanted to make sure they were aware of the system structure. They were asked to familiarize themselves with the system by trying out all possible actions and also to develop a strategy to control the functionality blindly. After that, the first of three test drives started. In the first two drives, the participants had to perform 12 actions. The researcher announced the task at intervals of 10 - 20 seconds. For the third drive, there were two blocks of changing the pre-selection and performing the basic interactions with the new setting. After each drive, participants completed a questionnaire. In the end, there was an additional concluding questionnaire. Overall, the study took about 70 minutes.

Independent and dependent variables The study was intended to gather mainly qualitative feedback on the concept and the use of hollows in general. We varied the *amount of visual attention* which was allowed to be directed towards the display. We used the DALI questionnaire [205] to measure workload, as well as AttrakDiff [99], SUS [32] and further questions to investigate the usability and suitability of the concept.

Hypotheses

H1: Hollows provide different meaningful interactions.
H2: Textures inside hollows support the localization of particular hollows.
H3: HollowWidgets' basic interactions can be executed blindly.

Results

User experience & usability Tasks were executed correctly in all conditions with only few exceptions. Hedonic and pragmatic quality of the system were rated to be in the top-right, desired corner of the AttrakDiff product portfolio, and therefore increased compared to the ratings of the previous study.

Usability was rated with an overall average of 74.58 points (of 100) on the SUS scale, which can be interpreted as a good to excellent product [14]. Additionally, we asked how well the functionality matched the respective actions, from *not at all* (1) to *extremely* (7). DRAG_IN, which was used to activate a widget, was rated with a mean value of 5.33 (sd = 1.56), DRAG_OUT for deactivation with 5.58 (sd = 1.38), and the adjustment of continuous values via ROTATE with 5.83 (sd = 1.47).

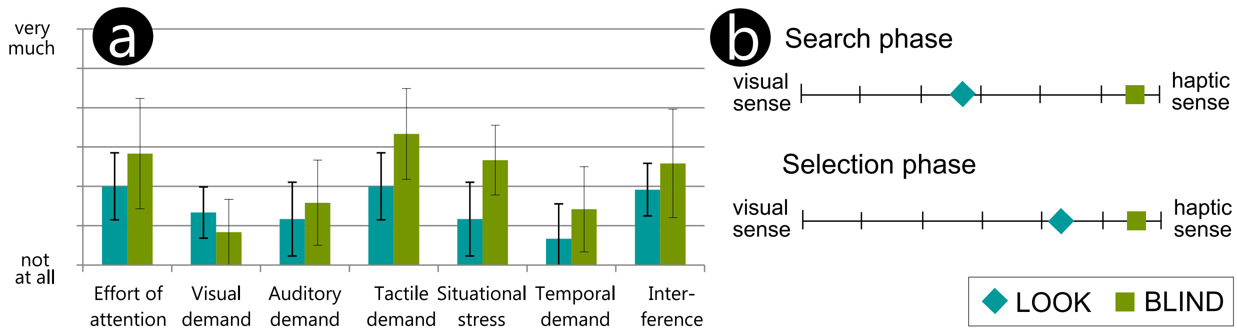

Figure 5.17: a: DALI measures on subjective workload. b: Estimations of the predominantly used sense.

Perceived workload The DALI questionnaire was completed after both LOOK and BLIND drives. Mean ratings were lower for all categories except visual demand when performing the task with occasional glances (LOOK, see Figure 5.17a). In the blind condition, observations and self-estimations indicate that participants did comply with the requirement to not look at the screen. They indicated to have used less than one glance for all 16 tasks ($m = 0.77$, $sd = 0.46$).

Distraction We asked the same subjective questions as in the preceding study on perceived distraction from the driving task, focus on the road and confidence in the non-primary interaction for both LOOK and BLIND condition. Overall, the task was more complex than in the former study where a mere selection of items had to be performed. This is reflected in the ratings. Comparing BLIND and LOOK condition, interaction was perceived significantly more distracting in the BLIND condition. However, participants felt they could attribute significantly more focus to the road scene than in the LOOK condition. The confidence in performing the task correctly was significantly lower for the BLIND condition.

We further asked which sense participants had mainly used for the search and selection phase. Figure 5.17b depicts that for the LOOK condition, the visual sense was employed for both tasks, but the use was significantly more extensive for the search phase (t = 6.92). Those required glances in the LOOK condition were said to be very short. This was sufficient for orientation in the search phase. Regarding the selection phase, most participants commented that this step could easily be completed without any additional visual attention. In the BLIND condition, participants interacted carefully to not trigger the wrong action. Together with the need to remember the respective item's position, this was commented to raise the mental workload in the search phase. However, this was not consistent for all participants: two individuals adopted the haptic orientation very quickly and used the system without looking towards the screen even if they were allowed to do so.

Preference Regarding the preference for shaped or flat surface, we did not provide a flat one for comparison; however, we assumed that everyone was familiar enough with touchscreens, as everyone indicated to use one every day. The aspects that were chosen in favor of the shaped surface with bends and hollows were that it enables blind control (10), and that it provides something to grasp for (2). 75% indicated to consider hollows to better support to look back to the road scene after an interaction, to lower the need to divert visual attention off the road and to raise the confidence when controlling the system. Overall, 75% would prefer hollows for control while driving in comparison with a flat surface.

Interpretation

The personalization of the interface in the beginning of the study was considered as a useful feature. Asked to choose between reasons of their arrangements, participants indicated that functional aspects such as *frequency of usage* (8) or *usual order* (4) had influenced their choice. Other perception-specific aspects such as haptic features were not stated.

The mappings of basic functions to gestures were considered as appropriate, so **H1** *(Hollows provide different meaningful interactions)* is accepted. For activation, the hollow would also have afforded tapping, which confirms to combine DRAG_IN with TAP.

We did not introduce the hollows' different tactile appearances but only asked whether they helped to identify the respective shapes in the end. Only three of the participants had noticed the different textures, and only four noticed the little bulge in one of the hollows. As a result, **H2** *(Textures inside hollows support the localization of particular hollows)* has to be rejected. From the observations, we found that participants focused more on coarse- than on fine-grained information for orientation. Asked for their strategy to interact with hollows in the BLIND condition, they named scanning over all hollows in combination with counting (10), starting either from the side border (6) or from the convex bend (4), and kinesthetic memory (4). When forced to avoid visual attention for localization, it seemed that the kinesthetic share of haptic exploration was preferred to a tactile exploration, at least when the tactile features are as little pronounced as in this prototype.

In the LOOK condition, most participants relied on a short glance for localization in the search phase (see Section 3.2.3), whereas the positioning was performed blindly most of the time. Similarly, the selection steps were predominantly performed with the visual focus on the road scene. Being forced to perform the interaction blindly seemed to result in a shift of visual attention towards an increased mental load for the localization task. Former research on gesture interaction has highlighted the potential to reduce visual distraction in terms of average and overall duration of glances; however, occasional short glances seemed to be required for orientation [10]. This is supported by our results, so **H3** *(HollowWidgets' basic interactions can be executed blindly)* is confirmed, with the restriction that it potentially raises mental load. Individual variations seemed to influence the behavior; we observed different preferences regarding full visual attention towards the primary task. In addition, there are different haptic abilities, which may be due to basic perceptual capabilities or learned cognition [174]. There were participants who did not look towards the screen even in the LOOK condition, while others commented it was extremely strenuous when they were forced to explore the interactive space haptically in the BLIND condition. An automotive user interface should support all different kinds of users and situations, and shaped surfaces can add further dimensions for multimodal interaction.

Essence The idea of *HollowWidgets* is to assign a restricted piece of functionality to an engraved hollow. Hollows, as representatives for static haptic features, offer a basic set of interactions; dragging gestures known from the previous study on selection approaches have been extended with a circular gesture along the border.
A driving simulator study showed that blind interaction is possible. The perception of the hollows' basic geometry enhanced with engravings enabled haptic perception. However, for the search phase, short orientation glances were preferred and reduced the perceived mental load.

5.4.4 Discussion

The previous two sections have introduced the use of hollows integrated into an interactive surface. First, we investigated how hollows can support a selection task (Section 5.4.2). Even in the TAP condition where no haptic exploration takes place, the shaped surface was preferred due to its ability to provide tactile feedback. Section 5.4.3 introduced *HollowWidgets*, a concept to offer rich functionality supported by the hollow structure. Basic interactions were considered to be useful and could be controlled blindly.

Overall, the two studies revealed two categories of users; the first did not attach great importance to absolute blind interaction but stated that a short glance for orientation on the screen would be acceptable. Hollows would then mainly serve to provide feedback on positioning and selection. In the first study, participants predominantly preferred DRAG_IN and suggested the described combination with TAP for selection. The second group was eager to have a system that can be controlled without any visual attention, and requested a system where incidental triggering is eliminated as good as possible. For selection tasks, they preferred DRAG_OUT and RIGHT_TAP, and in the second study they avoided visual attention even in the LOOK condition.

Moscovich [191] recommends to carefully discuss the trade-off between extra effort and the added value when using gestures instead of direct tap interaction. We saw that especially mental effort required to perform a certain action can limit the ability to focus on the driving task. A phenomenon we observed was that if visual distraction was reduced by replacing it with haptic perception, this can negatively affect mental load. Both has to be avoided while driving (see Section 2.1.2). Green [91] has defined *mind-off-the-road time* in addition to *eyes-off-the-road-time* when evaluating the effect of speech-based systems. If the interaction gets more complex, the visual attention might be directed towards the road, but the focus of attention can be elsewhere. Therefore, one needs to carefully avoid the application of overly complex gestures. For instance, we did not follow up with the RIGHT_TAP selection approach. Moreover, for future work, it will be interesting to see how the graphical user interface has to be designed to make orientation glances as short and effective as possible.

5.5 Lessons learned

The technology for non-flat surfaces is already available. Shaped devices in this chapter have been built based on rear projection on shaped diffuser planes and LCD technology with additional structuring layers. In addition, the next generation of OLED is likely to allow for non-flat geometries.

The evaluations showed that surface geometry can have an influence on the interaction and that interfaces need to be designed carefully to benefit from haptic features. Table 5.1 sums up the effects of shaped surfaces on the different steps of touch interaction (see Section 3.2.3).

For basic interactions such as **tapping and dragging**, we found that a convex bend can increase the overall subjective performance. This requires that the interaction includes a certain dwell time in which the finger is in contact with the surface so that a haptic exploration can take place. This was the case in the dragging task.

As a result, we further investigated the interaction with bends and hollows in combination with touch gestures. As an alternative to direct touch, selection can be performed by dragging across a characteristic feature of the respective shape. For **bend** selection, a downward dragging gesture served as a viable alternative for double tapping. Supporting a simple selection task with engraved **hollows**, we found that not only touch gestures, but also simple tapping benefits from the tactile feedback that is provided by the concave shape. We then introduced *HollowWidgets*, a concept to assign chunks of functionality to a set of hollows together with some basic actions for controlling it. A circular gesture along a hollow's border was successfully used to control continuous values. Dragging into or out of a hollow was investigated for activation and deactivation. Both search and selection phases could be completed blindly; however, when forced to interact blindly without occasional orientation glances, perceived mental workload increased. While some individuals preferred the usage with no visual distraction at all, most users preferred to have a short look at the screen to support the localization task.

We did not investigate shaped surfaces in a dynamic scenario. Further potential lies in the support for the interacting hand while driving, where car vibrations can lead to misplaced input. The proposed gestures allow that hand and finger can rest on the screen and not in midair. Moreover, particular surface shapes such as concave hollows can potentially provide advanced support to avoid that a finger slips off a taken position.

		Visual attention required for			
Phase	**Task**	**Simple touch**	**Tap & Drag**	**Bend selection**	**Hollow selection**
Search	1) Localization	x	x	x*	x*
	2) Positioning	x	x	(x)	(x)
Selection	3) Input	-	-	-	-
	4) Feedback	x	(x)	-	-

Table 5.1: Improvements through shaped interactive surfaces to simple direct touch regarding visual distraction. Details can be found in the text.

*) In the studies investigating bend and hollow selection, participants were able to localize the interactive areas blindly; however, there was a negative effect on mental workload.

Chapter 6

Conclusion and Future Work

Automotive cockpits are highly interactive - for instance, the latest 7 series BMW (see Figure 6.1) is equipped with about 40 hardware buttons in the center stack and a multifunctional controller in the center console. They are used to control a diverse set of functionality. This covers basic tasks of well established domains such as entertainment, navigation and climate control, but it also includes tasks such as answering an incoming call on a paired phone. Historically, some functions such as switching between different entertainment modes are assigned to a specific hardware button, while most others are displayed on the central information display (CID) and are controlled via the remote device. Apart from the hardware buttons, those cockpits are based on indirect control.

There are different approaches to introducing new forms of interaction. For instance, they rely on speech or gesture input, or aim to control content in a HUD with steering wheel controls. All of them have their respective benefits and drawbacks (see Section 2.1.3). A recent trend is to integrate interactive surfaces which have been shown to be advantageous compared to remote controls regarding ease of use, and efficiency of pointing and ballistic tasks (see Section 2.1.3). Moreover, they combine visual output with direct input (see Section 2.2). In their predominant manifestation, they are used for multifunctional mobile devices, namely smartphones and tablets. Such devices are small to medium sized, and lack haptic feedback due to a uniform, flat surface appearance.

This thesis addressed the problem that arises from the use of interactive surfaces for direct interaction: they hardly support haptic perception and thus increase visual distraction (see Section 2.1.3). Due to technological advances, interactive surfaces are *getting larger* and are *taking on new shapes*. Those two characteristics have already been investigated in other fields and have shown potential in targeting and the provision of tactile feedback (see Section 3.3 and 3.4). In this thesis, we have evaluated them with regard to their potential to decrease visual distraction.

Figure 6.1: Cockpit of a 7 series BMW 2013.[57]

6.1 Contributions

The goal of this thesis was to improve the design of interfaces on interactive surfaces. It focused on situations where visual load induced by a secondary task has to be kept as low as possible. The contributions take up the research questions stated in Section 1.2.2 and are based on the review of related work and the experimental part of this thesis.

6.1.1 Realizations of prototypical interfaces

Our analysis of both cars on the market and concept cars showed that interactive surfaces are being increasingly encorporated into cockpits. The prevalent manifestations are medium-sized, flat touchscreens, with a tendency to get bigger and better integrated into existing cockpit geometries. Chapter 4 and 5 described the design and technical realization of prototypical implementations, focusing on two upcoming physical aspects of interactive surfaces: *largeness* and *shape*. With this, we aim to inspire researchers with interaction concepts and technical approaches for prototyping.

Interaction concepts for large and shaped interactive surfaces in the car

Interactive surfaces can provide a platform for different user interfaces by means of direct touch and pointing interaction. By providing a digital interface, varying interaction and information needs, in different situations, can be satisfied.

The *SimplePlayer* prototype showed that position-independent touch gestures can ease the interaction by reducing the need to precisely touch the surface. Furthermore, existing or additional

[57] © Photos BMW Group.

hardware features such as knobs attached to the surface, or framing borders, can support spatial orientation (see Section 4.2). In *PointIt*, deictic gestures towards objects, inside and outside the car, were used to directly select objects for interaction (see Section 4.3). Large interactive surfaces as in *HelpMe* allow for separate interactive areas for driver and passenger, which can disburden the driver when handing over tasks (see Section 4.4).

With the *HollowSelect* prototype, we found that shaped interactive surfaces can be used to enrich direct touch feedback (see Section 5.4.2). Moreover, they enable new ways of interaction based on touch gestures, where interactive areas are emphasized by surface shapes such as sharp bends (*BendSelect*) or hollows (*HollowWidgets*) (see Section 5.3.3 and 5.4.3).

Prototyping non-flat interactive surfaces

While large interactive surfaces can be realized with off-the-shelf displays and a wide range of available gesture tracking systems, prototyping complex non-flat interactive surfaces is still a research topic. As a minor contribution, we present different prototyping approaches that have proven themselves in practice.

During the refinements of our shaped center stack in Chapter 5, we explored the creation of shaped **rear projected interactive surfaces** in combination with optical touch tracking. A laser projector was used for a sharp image in different depth planes. We found that FTIR illumination along the borders of bent acrylic glass (see Section 2.2.3) causes light leakage at the curvatures resulting in hot spots in the camera image. This was still applicable when the interaction was restricted to specific parts of the surface and individual thresholds could be set (see Section 5.2.1). However, to sense transitions from darker to brighter portions or vice versa, a DI setup is advisable (see Section 5.3.2). It enables sensing along and across bent curves. Moreover, it works with engravings that are added to the surface. Milled slots and laser-cut engravings allowed for precise and repeatable surface shapes. In contrast to existing rear projection prototypes, we did not add the diffuser layer to the front surface, but successfully applied projection paint to the flat backside of surfaces with engravings to avoid unevenly distributed paint (see Section 5.4).

Flat surfaces can be enhanced by adding an additional layer of material. In *BendSelect*, we showed that **silicon foil** is well suited to create perceivable structures in an early prototyping stage. It is self-adhesive and can easily be cut while still enabling capacitive sensing (see Section 5.3.3). Both its borders and elements placed between foil and screen can be explored for the interaction. In the *SimplePlayer* prototype, we introduced a haptic orientation point by attaching a fixed **physical control element** to a flat screen (see Section 4.2). This served to structure the displayed user interface and can be used in combination with the digital interface as an alternative input method. Several sensing approaches have been proposed: optical markers are beneficial when operating on a rear projected surface where vision tracking is already embedded [137], while recognition on capacitive screens can be based on conductive markers created by passive conductors [311] or active electronics [318].

6.1.2 Insights into the effect on visual distraction

To evaluate the effect of the different interface concepts on visual distraction, the first step of this thesis was to provide an analysis of the required steps for direct interaction (see Table 3.1).

Interaction is split into two main phases. In the **search phase**, the user has to *localize* the interactive element on the surface to know where the interacting finger needs to be placed. In the second step, the interacting finger has to be *positioned* correctly. In the **selection phase**, the user *performs the input* by touching the screen. Finally, the hand moves back and the user *perceives the feedback* provided by the system. For each step, we analyzed the need for visual attention based on a literature review (see also Figure 6.2).

Figure 6.2: Overview of the different steps that have to be performed for direct interaction.

Our different prototypes all aim to reduce the number and duration of glances by strengthening the role of haptic perception. They have been evaluated with regard to their influence on visual attention in each steps (see Table 4.1 and 5.1), in order to answer the following research question:

> **RQ1:** **How does the interaction with large and shaped interactive surfaces affect visual attention while driving?**

Localizing the interactive area

Glances required for localization were reduced in different ways. In the *SimplePlayer* study, we defined two different screen areas where the same touch gestures triggered different actions. Touch gestures did not require hitting the screen precisely. Participants only had to position their finger at an arbitrary starting point in an overall large area. Gestures were executed without a glance in 35% of trials. In the remaining trials, the average glance duration was significantly shorter than for both direct touch interfaces and a state-of-the-art remote controller. Localizing the correct area was based on haptic perception and participants used their spatial memory.

Moreover, we observed that participants were able to localize interactive areas blindly when they were supported by surface structure. In *HollowWidgets*, textures applied to the inner surface of the hollows were not distinct enough to identify a particular hollow. Participants relied on a coarse haptic perception, and applied different strategies such as scanning over the hollows from the side in combination with counting to localize a particular hollow. In those cases, localization and positioning coincided. Deprived of additional visual attention and focusing only on haptic perception, participants stated to be more focused on the road scene. However, when we allowed visual orientation, most participants used short occasional glances to extend haptic perception in order to gather an overview of the display area.

Positioning the interacting hand

In the evaluation of *PointIt*, participants required controlling glances to confirm the pointing direction when pointing at objects outside the car. This was not the case with the static interior pointing task we used. Participants were able to position their hand towards the glove compartment area blindly in 25% of cases based only on kinesthetic perception.

For the interaction with the *BendSelect* prototype, fingers were placed arbitrarily on the touch-sensitive surface, and optionally along a static haptic bend. Functions were automatically assigned to the fingertips. Re-positioning their fingers after placement was not required, so most participants left their hand in this position. In the study, we did not observe that subsequent glances towards the interactive surface were required.

Getting feedback on the interaction

Our experiments showed that static haptic structures can be used to confirm the correct positioning of a touch point. This was the case when using touch gestures in combination with shapes such as bends or hollows. Dragging across such a haptic element was defined to trigger an action. During dragging, the user could explore the surface's haptic features and react accordingly by adjusting the movement. Additionally, static haptic structures could also significantly raise the level of confidence of a basic tap interaction which does not include an exploration phase. The mere confirmation of a correct selection decreased the subjective need to turn the visual attention towards the interactive surface. Therefore, static haptics can enrich touch gesture interaction and serve as an additional modality to confirm basic direct touch interaction.

Moreover, the low number of glances when interacting with touch gestures in *SimplePlayer* indicates that interaction can be confirmed by kinesthetic perception. The participants felt their arm movement, so this type of interaction did not require additional feedback by the system.

Providing dedicated interaction spaces for the driver and the passenger showed improvements in all steps of the interaction. By passing tasks to the passenger, the input can be performed by him instead, and the driver does not need to directly interact with the interface. Moreover, the evaluation of *HelpMe* revealed the importance of always keeping the driver informed on the current state of the interaction, so that she does not lose her feeling of control.

6.1.3 Guidelines for the direct interaction with interactive surfaces

From the design and evaluation of the different prototypes, recommendations emerged on how to use large and shaped interactive surfaces to reduce the visual distraction caused by secondary interaction. This answers the second research question:

> **RQ2: How can interactive surfaces be designed to reduce visual distraction?**

Ease localization in direct interaction's search phase

Currently, orientation, which is required to localize a particular interface element, is predominantly visual. In contrast, the guidelines for physical control elements encourage providing haptically distinguishable features to support and signify different actions [90]. We suggest making use of different components of haptic perception to support or even substitute visual perception for this task.

Strengthen spatial memory On the one hand, kinesthetic perception, which senses variations in the orientation of the limbs, can be used for localization. Therefore, the respective interactive areas need to be large enough. Starting points for touch gestures in the *SimplePlayer* prototype could be placed in areas with a size of about $156\,cm^2$ without the need for visual attention. Smaller regions with a size of about $45\,cm^2$, which we had used for large touch buttons, could not be controlled blindly. This indicates that the minimal size must be somewhere between those two values.

Offer haptic orientation points On the other hand, haptic perception, as a combination of kinesthetic and tactile perception, can support the localization of different positions on a surface via active scanning and sensing for details. By providing distinct haptic features such as the centered physical control element inside an interactive surface (*SimplePlayer*), or varying textures in different parts of the screen (*HollowWidgets*), non-visual orientation becomes possible. Moreover, it then coincides with the second, positioning task. However, this comes at the expense of mental distraction. Our results indicate that particularly tactile perception increases subjective mental workload. This might be due to the linear nature of scanning as well as lack of experience and foresight with tactile cues on direct touch interfaces. We found that there are individual differences: some participants preferred to use haptic perception to support visual orientation, while others preferred the ability to rely entirely on their sense of touch.

Ease positioning in direct interaction's search phase

In the second step of the interaction, the finger needs to be positioned to be ready to perform the input on the surface.

Offer haptic guidance The finger can be guided towards the final position by haptic cues. An attached physical control element can not only help to locate the final position, but can also serve as a starting point for the interaction. Some fingers can hold on to it, while the remaining fingers can start to interact from there. Moreover, as presented in the *HollowWidgets* prototype, the finger can first be placed at the upper border of a hollow and then dragged into it as soon as the user wants to trigger the respective action.

Allow inaccurate positioning Another approach focuses on enlarging the interactive elements, so that the kinesthetic perception can confirm that the interacting arm and finger are positioned correctly. To enlarge the set of available actions, this can be combined with touch gestures as proposed by Ecker et al. [62] or Moscovich [191]. However, mapping directions to functions has been found to be ambiguous and might be too difficult to use blindly, resulting in an increase of mental workload.

Provide new techniques for interaction in the selection phase

Introduce new selection methods Shaped surfaces can open up new techniques for interaction. In combination with touch gestures, we proposed the selection of items by dragging across a haptic feature. In this way, dragging serves as a viable alternative for double tapping. It can be performed significantly faster and adds haptic feedback to the interaction.

The idea can be further extended: we[58] submitted a patent application to use this mechanism for hovering functionality [246]. On one side of the haptic barrier, a preview of the underlying functionality is presented. Dragging across the barrier triggers the respective action.

Provide rich haptic feedback in direct interaction's selection phase

Provide tangible targets In the last step of the interaction, shaped surfaces can provide feedback on the correct execution of a selection. By combining digital content with haptic features such as hollows (see Section 5.4), the tactile perception of the shape confirms the correct placement of a touch point or the process of a gesture when dragging across or along it. Therefore, we can add a new feedback modality to flat touchscreens. Similar to providing an auditory "click" feedback, haptic features serve to support the metaphor of pressing a button.

Map continuous motions to edges Moreover, the adjustment of continuous values with slider-like controls can be supported through shaped surfaces during the whole process of the touch gesture. Such controls can be placed along one-dimensional, preferably convex, bends, and also along the circular border of a hollow. To further enhance the feedback, one can add notches along a continuous shape, allowing the user to estimate their progress.

6.2 Future work

This thesis has provided a basic exploration of the properties *largeness* and *shape* for the interaction with interactive surfaces. Building on these results, research regarding different aspects can broaden the knowledge about how to design interfaces on these platforms. Moreover, one must not neglect how legislation will evolve in respect to the integration and usage of interactive surfaces.

Interdependency between visual attention, haptic perception and mental workload

Literature on distraction discusses visual, manual and mental distraction (see Section 2.1.2). From the results of our evaluations, we gained insights into the interdependency between visual attention, haptic perception and mental workload. If we ban visual attention for orientation within the user interface completely and reduce orientation to haptic perception alone, the user has to build a mental image only using haptic impressions. In our experiments, this led to an increased

[58] Patent application DE 102012211163.8 by Sonja Rümelin and Christopher Rölle.

mental workload. In our workshop on blind shape exploration (see Section 5.4.1), participants were surprised by the actual appearance of the objects after they were revealed. In particular, they underestimated the objects' size. This indicates that haptic perception might be better suited for extending, rather than replacing, visual perception for orientation and first exploration tasks.

Further investigations in the field of *cognitive psychology* should aim to measure the effects of varying shares of visual and haptic perception on mental workload in the different interaction phases. How much visual attention is required to decrease the negative effect of haptic perception? How should the different modalities be combined? Are certain tasks better suited for haptic perception than others? And how does experience with haptic interfaces affect those results?

Investigations of further shapes

For the investigation of interaction with shaped surfaces, we took examples of convex and concave bends as well as concave hollows. Our choice was based on related work, expert interviews and an exploratory workshop. This was, by far, not a comprehensive selection of possible shapes. However, for this set we showed that there are significant effects on the interaction. Those were, depending on the final embodiment, both positive and negative. This indicates that one needs to design such interfaces carefully so that performance will not be degraded.

Future research should analyze a *broader range of shapes*. On the one hand, there are many more general shapes defined by our design space (see Section 3.4), for example irregular bends or rectangular engravings that can be applied to interactive surfaces. On the other hand, one could focus on shape details and investigate them for instance with regard to just noticeable differences. This should be done in close cooperation with experts from the fields of *ergonomics* and *industrial design* and can be inspired by the design of traditional physical control elements and how they signify their underlying functionality. Moreover, solutions should incorporate general design principles to balance between functionality and aesthetics in an early stage.

Visualizations on large and shaped interactive surfaces

This thesis has focused on the input side of interaction on large and shaped interactive surfaces. The design of visual output on such display spaces has only been covered as far as it was required for the evaluation of our prototypes. Future research should aim to reasonably arrange and display content, for instance by assigning content to haptic features or by making use of the large human field of view [33].

Appropriate visualization strategies can reduce the distraction that may be caused by the interaction with those interfaces. Poitschke [213] has investigated different approaches to communicate critical situations to a driver interacting with a large CID. Fading out or locking content as well as presenting screen frames in different colors, resulted in increased primary task performance and decreased mental load.

We already started to integrate visual metaphors into our prototypes, such as dragging an icon into a hollow for activation or dragging a settings lens over a hollow to make adjustments in the *HollowWidgets* prototype. For other shapes such as bends, we imagine different metaphors that might support the user's mental model of the system. For instance, dragging an element at the convex peak of a bend can be emphasized by a fisheye visualization, or by using a clothesline as a metaphor to which elements can be attached. Thereby, the digital content can be associated with a meaningful combination of visual and physical representations which can in turn ease the interaction and decrease mental workload.

Dynamic material

Dynamically transformable material as envisioned by Ishii et al. [128] is an emerging topic which can influence future user interfaces, as it can help to adapt interfaces to a changing context. A drawback of static haptic features, as proposed in this thesis, is that they limit the flexibility of the interactive surface in which they are integrated. Dynamic haptic features, such as the inflatable buttons for touchscreens by Tactus[59], can offer haptic guidance on demand, for use cases such as keyboards or shutter buttons. Those haptic features can immediately disappear, for instance when a large flat surface is required again.

Future research should investigate how such a behavior affects the use of an interface's haptic support. One needs to carefully apply those new mechanisms to adjust the interface. If features constantly disappear, the user might become insecure as he can no longer rely on the feature support for orientation and positioning.

Legal issues

Seeing that the use of large touch-sensitive screens for automotive user interfaces has been increasing, public discussions have now started on whether or not these systems are legitimate.

In Europe, a Swiss prosecutor is considering to contest the permission of vehicle registrations for Tesla's Model S [139]. According to the present legal situation, the driver has to ensure that the infotainment system does not impact the attention dedicated to the driving task. However, Tesla's large display contains driving related functionality such as switching on the fog tail lamp, and it cannot be switched off. Moreover, there are other potential problems such as reflections. In the USA, the NHTSA has recently published recommendations which condemn the general integration of infotainment systems as a source of distraction [193] (see also Section 2.1.2). This becomes even more critical when the systems are getting larger. The agency states that content such as videos, photo realistic images such as satellite views of a navigation system, and the integration of news and social media services can potentially raise the driver's distraction level, and should thus be significantly restricted.

Public debates are progressing faster in the USA than in Europe. In summits for example hosted by the U.S. Senate Committee on Commerce, Science and Transportation, not only representatives of the NHTSA, but also of car manufacturers such as Toyota and General Motors and companies such as Google and Apple, discuss the current developments[60]. As a result, we expect technical guidelines that help to avoid distracted driving. This and court decisions on responsibilities for accidents will influence the decisions of all stakeholders regarding the integration of interactive surfaces and the functionality which is made available on them.

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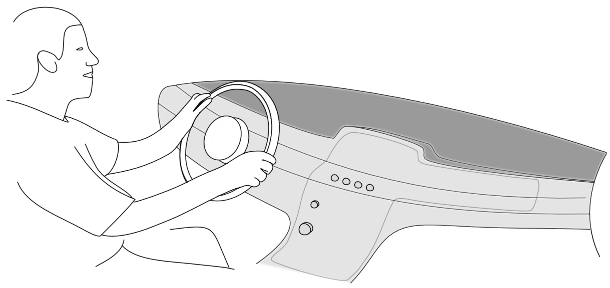
[59] `http://www.tactustechnology.com/technology.html` [cited 2013-12-17]

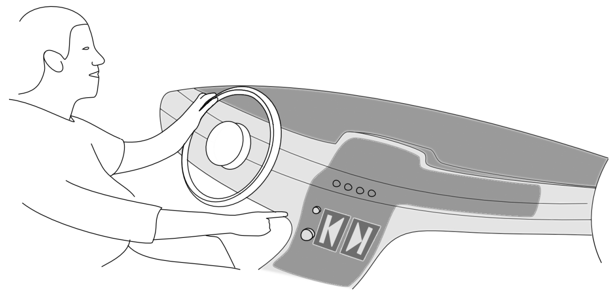
[60] `http://www.commerce.senate.gov/public/` [cited 2014-02-25]

6.3 Closing remarks

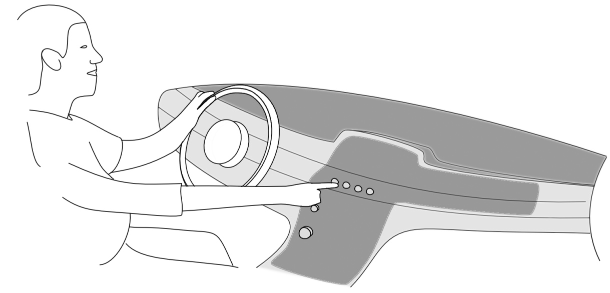
Emerging from this thesis, my vision of the *cockpit for the twenty-first century* is one that seamlessly integrates into the cockpit's geometry. It offers appropriate access to information and functionality while driving, but can also adapt to situations where the driver does not have to focus on the road, or when a passenger is present. This thesis has presented different aspects of this vision. What it did not provide was one prototype that brings it all together. However, the ideas and concepts evaluated in the preceding chapters can coexist, allowing the following story to become possible:



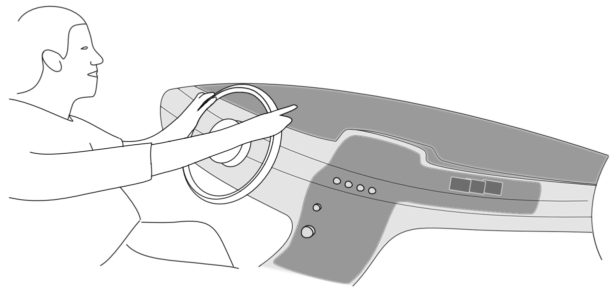
Pure driving – A cockpit needs to support the pure driving task. Infotainment functionality should then take a back seat. Large interactive surfaces can be part of the cockpit without attracting attention, for example by imitating the surrounding material.



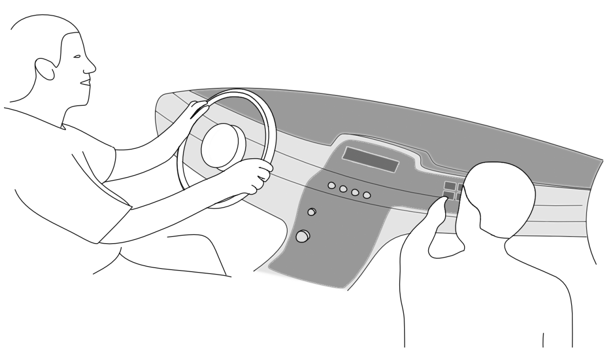
Quick direct control – In demanding driving situations, the driver still has access to some frequently used functionality such as basic music player functions. They rely on haptic support and spacious controls.



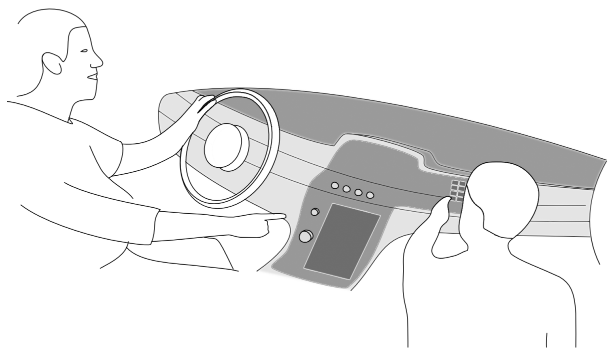
Static haptic support – For more complex secondary interaction, static haptic features on the screen allow the driver to explore the screen surface with the haptic perceptual channel. Those features define interactive areas, guide the interaction and provide feedback.



Interacting in the distance – The driver can directly interact with distant objects inside and outside the car. He can store selected POIs in the glove compartment area, and perform further detailed interaction with the help of shaped surfaces in his direct reach.



Driving with a passenger – Providing interactive surfaces that span over the whole width of the cockpit allows each person to have their own dedicated interaction space. When a passenger is present, he can take over some of the interaction. The driver is provided with a high-level overview and final results, but does not need to interact herself.



Supported by the passenger – Driver and passenger can have a shared interactive space where both can contribute to the interaction. Complex tasks such as text entry can be performed by the passenger. Final selection tasks can be passed over to the driver.

I believe that by embedding interactive displays into the surfaces of everyday, already existing objects, interaction can become more immediate than it is with many of today's remote systems and multi-purpose touchscreens. Providing tangible controls in combination with interactive surfaces may limit the flexibility; however, I think that rich objects will emerge that can provide meaningful mappings of physical objects with digital data. Haptic perception has been neglected when designing interfaces for flat touchscreens, but it has the potential to take away at least some of the visual distraction that is important for primary tasks such as driving.

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INDEX

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12. Juli 2011, § 8, Abs. 2 Pkt. 5.)

Hiermit erkläre ich an Eides statt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 25. März 2014

Sonja Rümelin