Supporting the Development Process of Multimodal and Natural Automotive User Interfaces

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Abstract

Nowadays, driving a car places multi-faceted demands on the driver that go beyond maneuvering a vehicle through road traffic. The number of additional functions for entertainment, infotainment and comfort increased rapidly in the last years. Each new function in the car is designed to make driving as pleasant as possible but also increases the risk that the driver will be distracted from the primary driving task. One of the most important goals for designers of new and innovative automotive user interfaces is therefore to keep driver distraction to a minimum while providing an appropriate support to the driver.

This goal can be achieved by providing tools and methods that support a human-centred development process. In this dissertation, a design space will be presented that helps to analyze the use of context, to generate new ideas for automotive user interfaces and to document them. Furthermore, new opportunities for rapid prototyping will be introduced. To be able to evaluate new automotive user interfaces and interaction concepts regarding their effect on driving performance, a driving simulation software was developed within the scope of this dissertation. In addition, research results in the field of multimodal, implicit and eye-based interaction in the car are presented.

The different case studies mentioned illustrate the systematic and comprehensive research on the opportunities of these kinds of interaction, as well as their effects on driving performance. We developed a prototype of a vibration steering wheel that communicates navigation instructions. Another prototype of a steering wheel has a display integrated in the middle and enables handwriting input. A further case study explores a visual placeholder concept to assist drivers when using in-car displays while driving. When a driver looks at a display and then at the street, the last gaze position on the display is highlighted to assist the driver when he switches his attention back to the display. This speeds up the process of resuming an interrupted task. In another case study, we compared gaze-based interaction with touch and speech input. In the last case study, a driver-passenger video link system is introduced that enables the driver to have eye contact with the passenger without turning his head.

On the whole, this dissertation shows that by using a new human-centred development process, modern interaction concepts can be developed in a meaningful way.

Zusammenfassung

Das Führen eines Fahrzeuges stellt heute vielfältige Ansprüche an den Fahrer, die über das reine Manövrieren im Straßenverkehr hinausgehen. Die Fülle an Zusatzfunktionen zur Unterhaltung, Navigation- und Komfortzwecken, die während der Fahrt genutzt werden können, ist in den letzten Jahren stark angestiegen. Einerseits dient jede neu hinzukommende Funktion im Fahrzeug dazu, das Fahren so angenehm wie möglich zu gestalten, birgt aber anderseits auch immer das Risiko, den Fahrer von seiner primären Fahraufgabe abzulenken. Eines der wichtigsten Ziele für Entwickler von neuen und innovativen Benutzungsschnittstellen im Fahrzeug ist es, die Fahrerablenkung so gering wie möglich zu halten und dabei dem Fahrer eine angemessene Unterstützung zu bieten.

Werkzeuge und Methoden, die einen benutzerzentrierten Entwicklungsprozess unterstützen, können helfen dieses Ziel zu erreichen. In dieser Dissertation wird ein Entwurfsraum vorgestellt, welcher helfen soll den Benutzungskontext zu analysieren, neue Ideen für Benutzungsschnittstellen zu generieren und diese zu dokumentieren. Darüber hinaus wurden im Rahmen der Arbeit neue Möglichkeiten zur schnellen Prototypenerstellung entwickelt. Es wurde ebenfalls eine Fahrsimulationssoftware erstellt, welche die quantitative Bewertung der Auswirkungen von Benutzungsschnittstellen und Interaktionskonzepten auf die Fahreraufgabe ermöglicht. Desweiteren stellt diese Dissertation neue Forschungsergebnisse auf den Gebieten der multimodalen, impliziten und blickbasierten Interaktion im Fahrzeug vor.

In verschiedenen Fallbeispielen wurden die Möglichkeiten dieser Interaktionsformen sowie deren Auswirkung auf die Fahrerablenkung umfassend und systematisch untersucht. Es wurde ein Prototyp eines Vibrationslenkrads erstellt, womit Navigationsinformation übermittelt werden können sowie ein weiterer Prototyp eines Lenkrads, welches ein Display in der Mitte integriert hat und damit handschriftliche Texteingabe ermöglicht. Ein visuelles Platzhalterkonzept ist im Fokus eines weiteren Fallbeispiels. Auf einem Fahrzeugdisplay wird die letzte Blickposition bevor der Fahrer seine Aufmerksamkeit dem Straßenverkehr zuwendet visuell hervorgehoben. Dies ermöglicht dem Fahrer eine unterbrochene Aufgabe z.B. das Durchsuchen einer Liste von Musiktitel schneller wieder aufzunehmen, wenn er seine Aufmerksamkeit wieder dem Display zuwendet. In einer weiteren Studie wurde blickbasierte Interaktion mit Sprach- und Berührungseingabe verglichen und das letzte Fallbeispiel beschäftigt sich mit der Unterstützung der Kommunikation im Fahrzeug durch die Bereitstellung eines Videosystems, welches Blickkontakt zwischen dem Fahrer und den Mitfahrern ermöglicht, ohne dass der Fahrer seinen Kopf drehen muss.

Die Arbeit zeigt insgesamt, dass durch den Einsatz eines neuen benutzerzentrierten Entwicklungsprozess moderne Interaktionskonzept sinnvoll entwickelt werden können.

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List of Acronyms

ACC – Adaptive Cruise Control

ALCT – Autonomous Lane Change Test

ACT-R – adaptive control of thought, rational

ADAM – Advanced Driver Attention Metrics

ADAS – advanced driver assistance system

ASR – automatic speech recognition

CAN – Controller Area Network

CARS – Configurable Automotive Research Simulator

DALI – Driving Activity Load Index

EIToolkit – Embedded Interaction Toolkit

IVIS – In-vehicle information system

JME – JMonkeyEngine

FOT – field operational test

GIDAS – German In Depth Accident Study

HCI - Human-computer interaction

HUD – Head-up Display

KLM – Keystroke level model

LCT –Lane change test

LWJGL – Lightweight Java Game Library

MI-AUI – Modeling interaction with automotive user interfaces

NASA-TLX – NASA task load index

NHTSA – National Highway Traffic safety administration

OEM – Original Equipment Manufacturer

PDT – peripheral detection task

POI – Point of Interest

TICS – transport information and control system

SAE – Society for Automotive Engineers

UMTRI – University of Michigan Transportation Research Institute

1 Introduction

1.1 Overview

125 years ago, the automobile was invented, and this was the beginning of a series of technological innovations to convert the simple means for transportation into a comfortable and safe vehicle that made driving a more pleasant experience. Whereas the car consisted in the beginning only of mechanical parts, nowadays many of the parts have been or will be replaced by electronic computing counterparts, such as steer-by-wire or other upcoming x-by-wire technologies. In 2008, Krum et al. stated: "The advanced automobile of today is a mobile computer equipped with interactive safety systems, including adaptive cruise control, collision warning signals, and automated lane keeping." [Krum et al. 2008].

For several drivers, cars have already become a place for media consumption (radio, MP3s, etc.), a personal communication center or even an interconnected workplace due to mobile phones and Internet access. Trends that led to this behavior while driving are the increasing capabilities and demand to have access to information always and everywhere and the improvement of sensor technology, which enabled the establishment of driver assistance functions that ease the driving task.

No matter how tempting it might be to include more and more functionalities in the car to enhance the driving experience and its fun factor, the primary task "driving" should never be placed out of the focus. All additional tasks create cognitive load; some "overload" by requiring too much interaction from the driver, and others "underload" by taking over parts of the driving tasks. Both types of tasks are highly likely to decrease driver's attention to the environment and focus on driving. Being engaged in additional tasks that are not related to driving is the main reason for car accidents [Dingus et al. 2006]. Therefore, it is essential while developing user interfaces for human-car interaction to make "reducing driver distraction" a general principle.

The work contributing to this dissertation was published over the last years in conferences and journals. The chapters are partly based on these publications, which are referenced at the beginning of each chapter. The most prominent parts of this research were published as full papers at Pervasive 2009 [Kern et al. 2009a], AutomotiveUI 2009 [Kern, Schmidt 2009] and CHI 2010 [Kern et al. 2010b].

The research reported in this dissertation is my own work. However, to highlight the teamwork that was involved in creating prototypes and systems, as well as conducting studies, the form of first-person plural (we) is used.

1.2 Human-car Interaction

Human-car interaction is basically a one-to-one relationship. Only one driver can maneuver one car at a given time. With the introduction of in-vehicle information systems (IVIS), advanced driver assistance systems (ADAS) or nomadic devices (systems that are not integrated into the car, e.g. cell phones, laptops and external GPS systems), there has been a shift towards one driver operating one car and many devices. It is evident that driving was always more than the maneuvering of a car. The driving task can be divided into three classes: primary, secondary and tertiary [Geiser 1985]. Primary tasks describe how to maneuver the car, e.g. control the speed or check the distance to other cars or objects. The steering wheel, which is the most well-known primary control, and the pedals are the earliest control devices introduced in the car. So far, these devices have remained largely unchanged – additional controls are often mounted on the modern-day steering wheels – and can be considered an integral part of the car. However, it is worth pointing out that there is ongoing research in replacing the steering wheel with alternatives, e.g. a joystick [Kienle et al. 2009]. Secondary tasks are functions that increase the safety of the driver, the car and the environment, e.g. setting turning signals or activating the windshield wipers. Tertiary tasks are all functions regarding entertainment and information systems. This dissertation's main focus is on human-car interaction in the tertiary task domain.

Although the computing power of systems integrated in the car is comparable to current mobile phones or even desktop computers, interacting with these systems is very different. Commonly used input devices for the desktop domain, such as mice, keyboards and large information-rich displays for presenting output, are not feasible in the car. Human-car interaction is subject to different restrictions that generally do not apply to human-computer interaction (HCI).

Whereas a user is able to provide his full attention to a computer system in a desktop environment, a driver always has to share his attention between the primary task and other non-driving-related activities. When the primary task is not fully attended to, dangerous situations may arise. Thus, the primary task has to have the highest priority, and tertiary tasks have to play minor roles.

In a desktop environment, the user is more or less free to choose with which body part he wants to interact with the computer. He can operate the mouse with the left or right hand or even with his feet if he wants to. In the car, however, the driver is in a constrained posture. He is buckled up in the driver's seat and is very restricted in mobility. He can only interact with devices that are in his operating distance. For example, he cannot use a multifunctional controller mounted in the center stack in a left-hand drive vehicle with his left hand. He would be forced to use the right hand to operate this device, since his left hand would not reach it without extreme and potentially unsafe body movements. Furthermore, two-handed operations are not acceptable; for safety reasons, one hand should always remain on the steering wheel [European Communities 2007].

The environmental conditions while using a desktop computer do not affect human-computer interaction in a critical way. A user might be disturbed by environmental noise or light conditions, but it is not known that this has ever put the user or others in his vicinity in a dangerous situation. Human-car interaction, on the other hand, is always use in context, where the current driving situation greatly affects the interaction. For example, interacting with an entertainment system under high traffic conditions might result in higher workload for the driver, be it physically, visually or mentally, than while driving on an empty highway. A task that seems to be suitable in one situation might not be acceptable in another, where it might put the driver and others around him in danger. The user has to decide if the task he wants to perform while driving is appropriate in the given situation.

There are also some differences in the development process of creating new automotive user interfaces, which are not just due to the differences in interacting with computer systems in the car versus in a desktop environment. While applications for a desktop computer can be tailored to a specific target group and to a concrete use case, user interfaces in cars have to be designed in a way such that a vast amount of different users are able to use it. The typical age of drivers ranges from 16 to over 80. 80% of the 21-year-old age group have a driver's license and that number stays on a similarly high level until the mid-70s age group [Green 2002]. Some user studies showed that drivers that are over 65 years old need one-and-a-half to twice the time to perform a task than younger drivers [Green 2002]. This is one important fact that has to be considered while designing new interfaces for tertiary tasks in the car and also while evaluating them. Other differences can be seen in the long development cycles. Developing a new car model takes usually up to several years. That means a new user interface might be out of date (compared to the usual lifetime of desktop applications) before it actually becomes a real product. This difference is even greater when comparing the long lifetime of a car to that of a PC or mobile phone. Furthermore, up to now there has not been a simple way to update the current version of an automobile system like it is commonly done for desktop or mobile phone applications.

Evaluating the usability of an automotive user interface includes ethical considerations, because the risk of an accident is always present. Whereas a trial-and-error approach for evaluating a new user interface might be an option for a desktop application that is already on the market, this approach is unacceptable for automotive user interfaces, since it might have fatal consequences [Schmidt et al. 2010]. Therefore, it is essential to perform tests and studies first in a simulator before taking the system on the road in order to safely estimate the effect of a new automotive user interface on driving performance.

New technical developments, be it new driver assistance systems or the opportunity to have access to the Internet and thereby to a huge amount of data, create new problems. Information has to be presented in a way that does not overload the driver. On the other hand, the shifting of most driving tasks to ADAS may lead to the driver being underloaded and lead drivers to shift their attention away from the road scene to other activities in the car. Reactions to unpredictable events that require the driver to override ADAS and take charge of the primary task may be delayed.

1.3 HCI Challenges for Automotive User Interfaces

The main challenge for automotive user interfaces is to create them in a way that they do not negatively affect driving performance and enhance the driver's experience; ideally, they would make driving safer but still provide a valuable service. Furthermore, tools and methods are needed to prove that new automotive user interfaces are suitable for use while driving. In this section, a few human-car interaction challenges, as well as challenges for the development process of automotive user interfaces, will be presented.

Interacting intuitively and naturally is probably users' most preferred way of interacting with a computer. No training or manuals are needed to use such an interface, and in the car context, such an interface helps to maintain safety. User interface designers utilize implicit interaction techniques to make interfaces more natural. One challenge for automotive user interfaces is to integrate new modalities into the car, e.g. eye tracking enables natural and implicit input to the system and thereby reduces the driver's cognitive load.

With many new interaction technologies, designers have more and more options in creating user interfaces. In many other domains, ranging from PCs to gaming devices and mobile phones, providing multimodal user interfaces has helped to increase usability and enjoyability of systems. User expectations have changed due to this and multimodal user interfaces should be available everywhere. Hence, in cars we see more and more efforts to offer new or alternative modalities, essentially creating multimodal user interfaces. Supporting the design and development of multimodal interfaces in the car is another central challenge.

From the beginning, cars were constructed in a way that not only the driver but also some passengers could be transported. That makes driving often a social event. On the one hand, the presence of passengers is accredited to increase driving safety by having an extra set of eyes and ears watching the road [Rueda-Domingo et al. 2004]. On the other hand, passengers are seen as the source of distraction by giving the driver a reason to take his attention off the road [Lerner et al. 2007]. Usually while driving with passengers, the driver is engaged in a conversation or discussion. A further challenge for human-car interaction can be seen in providing entertainment for passengers and in supporting natural interaction between the driver and the passengers without taking the driver's attention off the road.

The differences between human-computer interaction in the desktop or mobile devices domain and human-car interaction result in additional requirements for the design development process. In ISO 9241-210 [ISO 9241-210:2010], a human-centred design process for interactive systems is proposed (see Figure 1). Although the car context has different requirements in the design cycle steps, the car has become a computer-based interactive system as well. Therefore, we are convinced that the proposed design process is also applicable for automotive user interfaces. We analyzed the design cycle for developing an interactive automotive systeem and added specific requirements for the automotive context, see the green boxes in Figure 1.

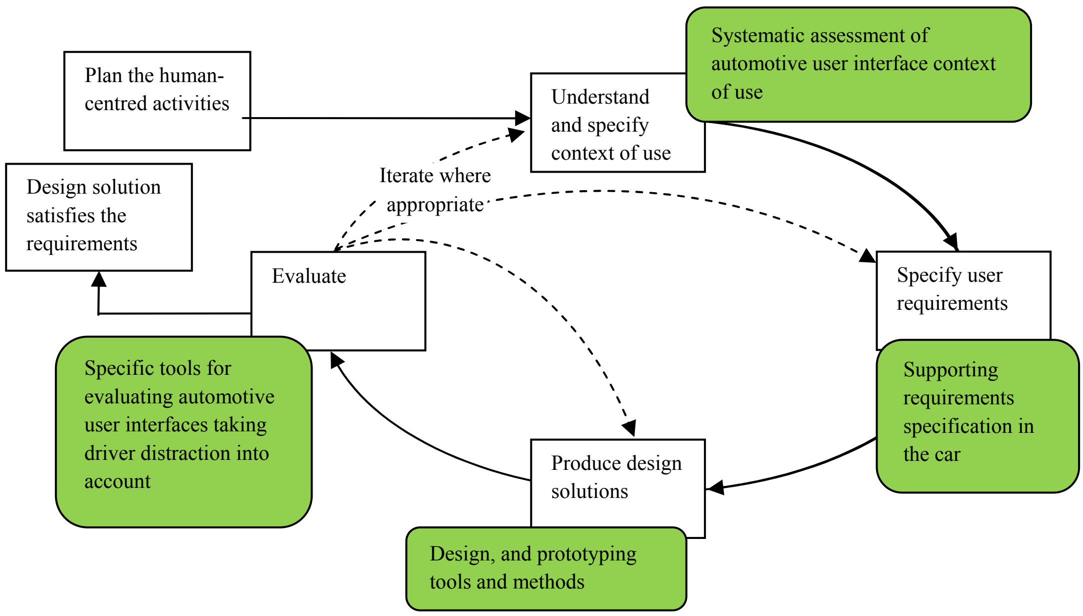


Figure 1. Human-centred design process according to ISO 9241-210 [ISO 2008]. The green boxes at the specific activities indicate additional requirements for developing automotive user interfaces.

Historically, car manufactures and their part suppliers developed user interfaces and the required devices, but now, many manufacturers and companies that provide software and nomadic devices have designed systems that would possible to use while driving. The need for providing standardized interfaces for connecting such devices to the car is increasing by the number of personal devices that drivers want to use while driving. Downloading apps from an app store to a mobile device is nowadays a common approach and will probably soon be possible for the car as well. Finding a means for analyzing and documenting automotive user interfaces is a central challenge, especially when considering the huge number of parties that are now involved in the development process. This means should be applicable in all stages of the design process.

Particular attention is paid to the evaluation of new automotive user interfaces. A main challenge for the development process of automotive user interfaces is to provide safe methods for qualitative as well as quantitative measures. These measures are needed to help decide if a novel user interface can be recommended for the use while driving when taking driver distraction into account. Another challenge is keeping up with the fast pace of software development and the apps culture. Rapid prototyping and quick evaluation methods are required to decide quickly which user interface idea is it worth pursuing and which idea would distract the driver too much from his primary task.

1.4 Scope, Aims and Methods

The objective of the research presented in this dissertation is to explore the design space of automotive user interfaces, as well as opportunities to support the human-centred design process of novel automotive user interfaces. Two kinds of user interfaces and their practicality for use while driving were investigated in more detail: multimodal and implicit user interfaces.

One aim is to offer a scheme for describing automotive user interfaces in a consistent way, which serves as a basis for discussions and for generating new automotive user interface ideas. Another goal is to create tools and methods that help to ease the development process. Demonstrating the usefulness of an eye tracker for implicit input in the car, as well as providing further insight into the utility of multimodal input to automotive user interfaces, are further goals.

Methods used to achieve the goals include taking, collecting and analyzing about 750 photographs of car cockpits from different car models, designing and implementing prototypes of new user interface ideas to assess their effect on driver distraction, and creating methods for supporting the development and evaluation process. Furthermore, evaluations of the proposed ideas were conducted with both quantitative and qualitative measures.

1.5 Contributions

The main contributions of this dissertation are:

- A comprehensive design space of driver-based automotive user interfaces and its graphical representation for supporting developers in each stage of the design process, specifically to understand the context of use, to extract user requirements, to generate ideas, and to document design decisions.
- Design and implementation of CARS (Configurable Automotive Research Simulator), an open source driving simulator software for evaluating automotive user interfaces that offers built-in functions for estimating driver distraction.
- Design and implementation of MI-AUI (Modeling interaction with automotive user interfaces), a rapid prototyping tool that allows virtual as well as the first tangible prototypes to be built and predicts user performance using an adapted keystroke level model.
- Demonstration of the usefulness of the EIToolkit (Embedded Interaction Toolkit) for rapid prototyping of automotive applications by utilizing it in various case studies.
- Prototypes and user studies that explore the challenges of multimodality, implicit interaction and communication in the car, creating new insights into the creation of novel automotive user interfaces.

1.6 Thesis Outline

After the introduction of important terms and an historical overview of automotive user interfaces, the phenomenon of driver distraction is described and the guidelines and norms that may help to develop good user interfaces for use while driving are discussed. At the end of chapter 2, evaluation methods for automotive user interfaces are presented.

In chapter 3, the design space for driver-based automotive user interfaces is introduced. After an examination of input and output devices in the car, the graphical representation of the design space is illustrated and substantiated with several examples.

Chapter 4 focused on multimodality in automotive user interfaces. After addressing the term “multimodality”, related work on tactile output and handwriting interaction in the car are discussed prior to introducing two case studies. In case study 1, multimodal output information for navigational instructions are provided. Vibro-tactile output on the steering wheel is combined with visual output in the center stack and/or audio output. Case study 2 focuses on multimodal input/output by exploring different positions of handwriting input. Input on the steering wheel is compared to input in the horizontal center stack. Output was given either on the steering wheel, on the horizontal center stack, or on the vertical center stack. A discussion of the impact of our proposed ideas on driving and driver distraction completes this chapter.

Chapter 5 is structured similarly to the previous chapter but focuses on implicit as well as gaze-based interaction to make automotive user interfaces more natural. After explaining the meaning of implicit interaction, related work on implicit interaction in the car, as well as on gaze tracking is provided. The physical driving simulator setup that is used in all case studies is presented next and the descriptions of the three case studies follows. Case study 3 presents the design, implementation and evaluation of *Gazemarks*, a concept for easing attention switching by highlighting the last area of the screen on which users fixated before moving their attention away. This visual placeholder helps to ease orientation and resumption of the interrupted task when coming back to this screen. Case study 4 compares three different input techniques: speech input, touch input and gaze input. Prototypes for each input modalities were created. For gaze-based interaction, users highlight an item on the screen by looking at it and select it by pressing a button on the steering wheel. Social aspects while driving a car are addressed in case study 5. A driver-passenger video link system enables driver and passenger to have eye contact without the need to move driver’s eyes completely away from the forward roadway. Gaze-based interaction is used for activating a video image of the backseat passenger in a head-up display (HUD). As in the previous section, a discussion about the impact on driving and driver distraction is given at the end of this chapter.

Chapter 6 presents methods and tools for supporting the human-centred development process of automotive user interfaces. In the first section, the usage of the design space is demonstrated with a graphical representation of a concept car that offers all user interface ideas proposed in this dissertation. Afterwards, the prototyping tool MI-AUI (Modeling interaction with automotive user interfaces) is introduced. In most of the case studies, the EIToolkit for rapidly creating prototypes is used. EIToolkit’s utilization in the development process is demonstrated in the next section followed by a description of the design, implementation and evaluation of CARS (Configuration automotive research simulator). CARS consists of three components (Map Editor, Simulation Tool and Analysis Tool) for assessing the impact of tertiary tasks on driving performance, especially in early stages of the prototyping cycle. When using CARS in these early stages, automotive user interface designs that would cause high driver distraction can be quickly excluded from the design process.

The conclusion in chapter 7 summarizes the content and main contributions of this dissertation. In the future work section of this chapter, new issues that arose during this work are discussed.

2 Background, Fundamentals and Related Work

2.1 A brief History and Overview of User Interfaces for Cars

The invention of the wheel in about 400 B.C. created the basis for the car as we know it. However, it took more than 2200 years before the first motor vehicles were introduced by Gottlieb Daimler and Carl Benz in 1886. The automobile was not invented in a single day by a single inventor. Its history reflects an evolution that took place worldwide. The timeline illustrated in Figure 2 gives a short overview about the development of motor vehicles. At the beginning, the main focus was on providing a more or less comfortable, universal and individual means for transportation. Early cars only consisted of devices for the primary driving task (steering device and pedals). With the introduction of the steering wheel in 1898, all primary task devices that we can still find in modern cars were defined [@citroenet]. With the opportunity to drive faster and the increasing number of cars the need for safety grew. The first secondary task device, the windshield wiper, was introduced in 1903 [@MIT_WEB]. At first, this device was still operated by hand, but in 1917, an automatic electronically-operated version was introduced [@carhistroy4u]. The invention of the turn indicator in 1929 was a reaction to the need for traffic regulations caused by the increasing number of cars [@carhistroy4u]. With the installation of the first radio in cars in 1929, the entertainment domain found its way into the car as a third class of devices [@inventors(2)]. Last but not least, with the introduction of digital maps for GPS navigation systems at around the turn of the millennium, colored displays were installed to provide the driver with position information. Understandably, these displays were soon used for providing other visual information, e.g. radio channels or heating adjustments. With the introduction of new functions in the car, be it for a primary, secondary or tertiary task, the complexity of interacting with these functions increased.

Whereas the number of primary task devices has not changed in the last 100 years, the amount of tertiary task devices increased rapidly at first until it became clear that a one-to-one mapping from control to function was not possible anymore. For this reason, there is an observable trend in automotive systems where different functions are combined in infotainment and entertainment systems, which usually consist of either a touchscreen or a single controller and a display. For example, a BMW series 7, built in 2008, has about 700 functions only for entertainment, telephone, climate and navigation that are integrated into the iDrive system [@Businessweek 2008].

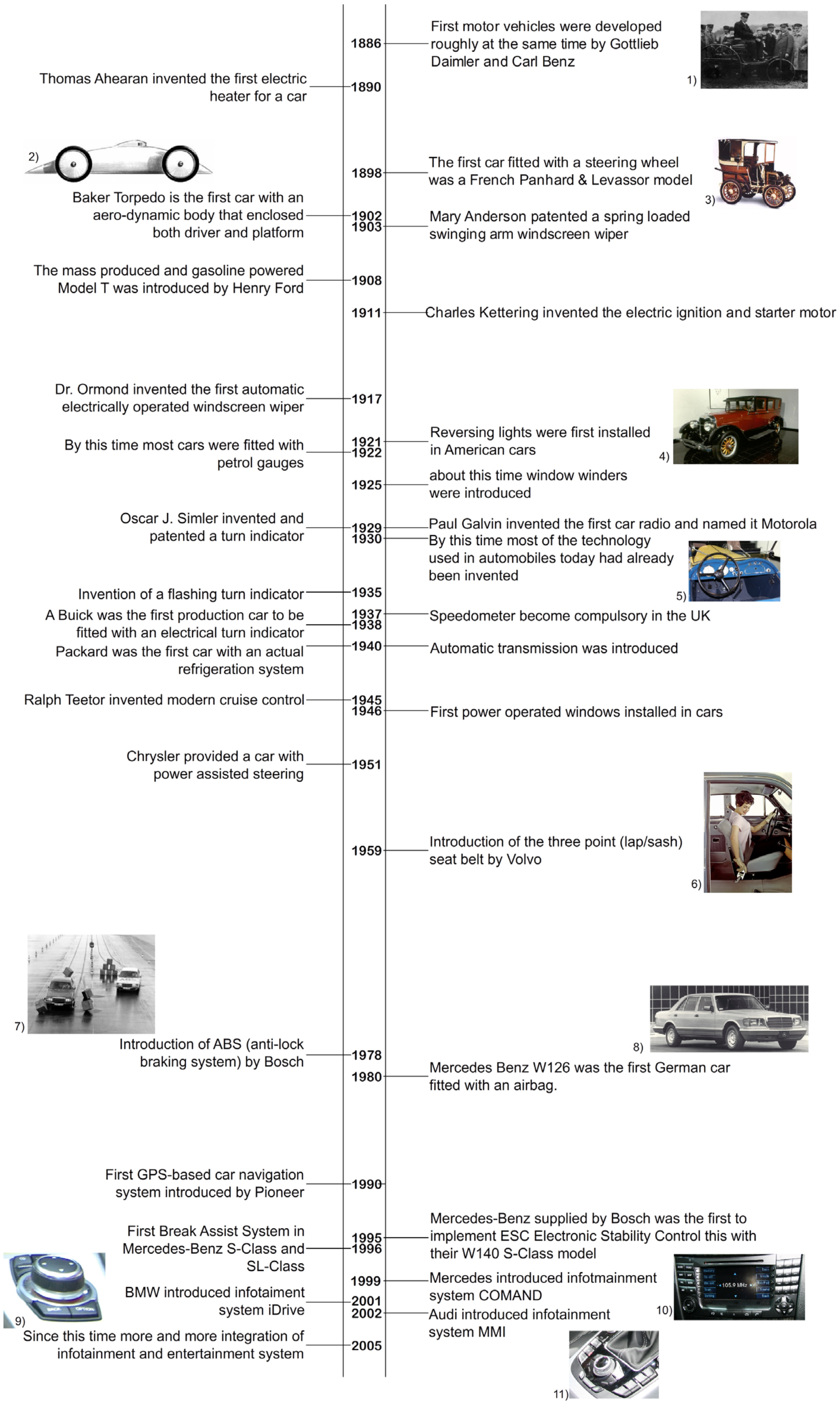


Figure 2. Timeline of the development of motor vehicle especially regarding user interfaces based on information found on the web [@carhistroy4u; @DiscoveryChannel; @earlyelectric; @inventors(1); @inventors(2); @MIT; @PBS; @Pioneer; @Wikipedia(1)] and in [Schindler, Sievers 2007]. Picture credits: 1) [@Wikipedia(2)], 2) [@the-blueprints.com], 3) [@citroenet], 4) [@finecarsforsale], 5) picture taken at BMW museum Munich 2009, 6) [@Mailonline], 7) [@automobilesdeluxe], 8) [@NetCarShow], 9) picture taken at IAA 2009, 10), 11) pictures taken at IAA 2007.

This trend of combining functions into a central system leads to a reduced number of different interaction devices, but requires the driver to search through different menus to find a desired function. In some cases, this is not ideal, e.g. searching for the menu function that changes the radio volume might be annoying for the driver. Thus, there is a tradeoff between how many functions are quickly accessible and how overloaded the user interface is. This tradeoff can be observed in many current car interface designs.

Car cockpits shown in Figure 3 illustrate the physical evolution of the driver's workplace, taking different BMW models as an example.

Figure 3. Car cockpits of BMW cars from different years illustrate the evolution of automotive user interfaces. Pictures taken at the BMW museum in Munich 2008 and at IAA Frankfurt 2009.

Nowadays, beside the built-in devices, drivers bring a lot of personal devices for infotainment and entertainment into the car. Car manufacturers try to provide a means for integrating these nomadic devices physically, e.g. by providing Bluetooth interfaces, and virtually, by including external personal content like music playlists in their infotainment and entertainment system. Researchers are also looking at how to integrate car functions into non-driving contexts, e.g. making car information available on a phone or providing functions to control cars with mobile phones, such as locking the door. The first products are already available on the market [@connect2car]. The movie industry already showed in "James Bond –Tomorrow Never Dies" (1997) how James Bond controls his car via a mobile phone. This fictional scenario became reality in 2009 when researchers from the University of Berlin developed iDriver–an iPhone remote controlled car [Wang, Ganjineh 2010].

2.2 Definitions of Terms

There are several views on the workplace of a driver, among which different terms are used. Thus, definitions for two terms that are relevant in later chapters are clarified briefly in this section.

Different terms can be found in the literature to describe the user interface, with which the driver interacts while driving. The most commonly-used terms are "in-vehicle user interface", "in-vehicle interface", "in-car user interface" and "automotive user interface". All of them mean the same thing, and in our work, we mainly use the term "**automotive user interface**".

Additionally, in the research field of automotive user interfaces, there are two different meanings of the term "secondary task". As already mentioned in the introduction the driving task can be divided into three classes: primary, secondary and tertiary tasks [Geiser 1985]. According to Geiser, secondary tasks refer to functions that aim to increase the driving safety, e.g. turn on the headlights. But oftentimes the term "secondary task" is also used to specify the additional tasks that the driver performs while driving, including eating, drinking, communicating with passengers and interacting with infotainment and entertainment systems. In user studies, secondary tasks often describe the tasks to be analyzed. In our research, we apply Geiser's definition. In all of our reported studies, **interaction with infotainment and entertainment systems** are referred to as **tertiary tasks**. Nevertheless, when referencing related work according the intention of the authors, the term "secondary task" is used as a collective term of additional tasks in the car. In such cases, we used the term "secondary in-vehicle task" to differentiate it from our usage of the term "secondary task".

2.3 Driver Distraction

The first concerns about driver distraction arose already in 1913, when windshield wipers were introduced. Researchers feared that the wipers would hypnotize the driver [Vermette 2010]. Nowadays, there are many things that can distract the driver from the driving task. Stutts et al. [Stutts et al. 2001] identified several sources of driver distraction, such as eating/drinking, outside person/object or event, interacting with entertainment systems, other vehicle and talking/listening on the mobile phone. These sources can be divided into internal and external sources of distraction and then further into driver-initiated and non-driver-initiated [Pettitt et al. 2005]. An example of an internal driver-initiated distraction is making a phone call. An unpredictable action of a passenger can be classified as an internal non-driver source for distraction. External non-driver initiated source for distraction is, for example, an unpredictable behavior of another driver or a pedestrian. A driver looking for a specific house number can be seen as an external driver-initiated source for distraction. Sources of driver distraction can also be classified as technology-based distraction (mobile phones, navigation systems, in-vehicle Internet, etc.) and non-technology-based distraction (eating and drinking, smoking, passengers, etc.). Even though driver distraction can be clearly illustrated with examples and classifications, it is hard to find a generally accepted definition that includes all aspects of driver distraction in the literature. Two definitions of driver distraction that cover many different definitions given by researchers (many of which are summarized in [Kircher 2007]) will be addressed in the remainder of this section.

After the first conference of "Distracted driving", held in Toronto in October 2005, Hedlund et al. suggested in a summary paper of the conference the following definition:

> *"Distraction involves a diversion of attention from driving, because the driver is temporarily focusing on an object, person, task, or event not related to driving, which reduces the driver's awareness, decision-making, and/or performance, leading to an increased risk of corrective actions, near-crashes, or crashes." [Hedlund et al. 2006]*

In the literature, four types of distraction are recognized: visual, auditory, physical and attentional distraction [Young et al. 2003]. Visual distraction occurs when the driver looks at another visual target (e.g. a navigation map) instead of the road. Auditory distraction occurs, for example, when the driver listens to the radio or talks with passengers or on the phone so that auditory signals from the road environment are masked. Removing one or both hands from the steering wheel to interact with an object is called physical or biomechanical distraction. The last form, attentional or cognitive distraction, occurs when the driver takes his attention off the road, e.g. when he is engaged in conversation with a passenger or on the phone. Pettitt et al. include these four types of distraction in their definition:

> *"Driver distraction occurs when:*
>
> - *A driver is delayed in the recognition of information necessary to safely maintain the lateral and longitudinal control of the vehicle (the driving task)* ***(Impact)***
> - *Due to some event, activity, object or person, within or outside the vehicle* ***(Agent)***

- *That compels or tends to induce the driver's shifting attention away from fundamental driving tasks **(Mechanism)***
- *By compromising the driver's auditory, biomechanical, cognitive or visual faculties, or combinations thereof. **(Type)"** [Pettitt et al. 2005]*

According to Stutts et al. [Stutts et al. 2001], drivers who are distracted tend to do 3 things. First, they react more slowly to traffic conditions. Second, they fail more often to recognize potential hazards, such as pedestrians. Third, they have a decreased margin of safety. To compensate for any decrease in attention to the driving task, drivers try to self-regulate their driving. Young et al. [Young et al. 2007] give an overview of compensatory and adaptive behavior that has been reported in the literature. The behavior can be seen on a strategic level (e.g. choosing not to answer a mobile phone) or an operational level (e.g. decreasing speed, increasing inter-vehicular distance or checking the instruments less frequently). Nevertheless, it is not uncommon that driver distraction is the cause of car accidents.

2.4 Driver Distraction – One Cause of Car Accidents

The German „statistisches Bundesamt" publishes annually accident statistics about police-reported traffic accidents in Germany. About 2.4 millions car accidents were reported to police for the year 2010, of which about 2.1 millions caused property damages and about 288,000 caused injury to persons. 3,651 people died in a car accident in 2010 [Bundesamt 2011]. A limitation of these statistics is that very little information about how accidents occur is available; only the cause of the accident – crash-related (e.g. weather conditions), car-related (e.g. technical defect) or person-related (e.g. drunk driver) – is available. Since 1999, GIDAS (German In Depth Accident Study) [@GIDAS] collects extensive information about the pre-accident, collision, and post-accident phases and compiles this data in a database. Similar databases (e.g. FARS - Fatality Analysis Reporting System [@NHTSA]) are provided by NHTSA for the USA. Detailed information about driver distraction is collected, e.g. distracted by other occupant, by moving object in vehicle or while talking or listening to cellular phone. Although these statistical databases can be very valuable for improving the safety of cars, the pre-accident information is still self-reported by the driver and therefore varies in their credibility. Especially negative behavior tends to be unreported and information about driver fatalities is missing. In contrast, observational studies provide great detail about driver behavior and activity before and at the time of the crash.

The largest observational study is called 100-Car Naturalistic Driving Study [Neale et al. 2005; Dingus et al. 2006]. This study tracked the behavior of drivers of 100 vehicles for more than one year. A primary goal was to provide pre-crash data for understanding causes of crashes. All cars were equipped with sensors and video devices to collect data. Sensors provided the following data: longitudinal and lateral kinematic information, information about leading or following vehicles, information about lateral conflicts, and information about lane-keeping behavior. Five cameras monitored the driver's face and side of the vehicle, the forward view, the rear view, the passenger side, and a view of the driver's hands and surrounding areas. The drivers were given no special instructions and no experimenter was present so that the observation would be unobtrusive. In the end, researchers had to analyze almost 43,000 hours of data that covered 2 million driven miles from 241 primary and secondary drivers. Events that occurred over the one-year time period were categorized as crashes ("any contact between the subject vehicle and another vehicle, fixed object, pedestrian pedacyclist, animal"), near crashes ("defined as a conflict situation requiring a rapid, severe evasive maneuver to avoid a crash") or incidents ("Conflict requiring an evasive maneuver, but of lesser magnitude than a near crash") [Neale et al. 2005]. The 241 drivers were involved in 82 crashes, 761 near-crashes, and 8295 critical incidents. A benefit of the naturalistic approach is that it was possible to record crashes that were not reported to police. Of the 82 crashes recorded in the study, only 15 were reported to the police.

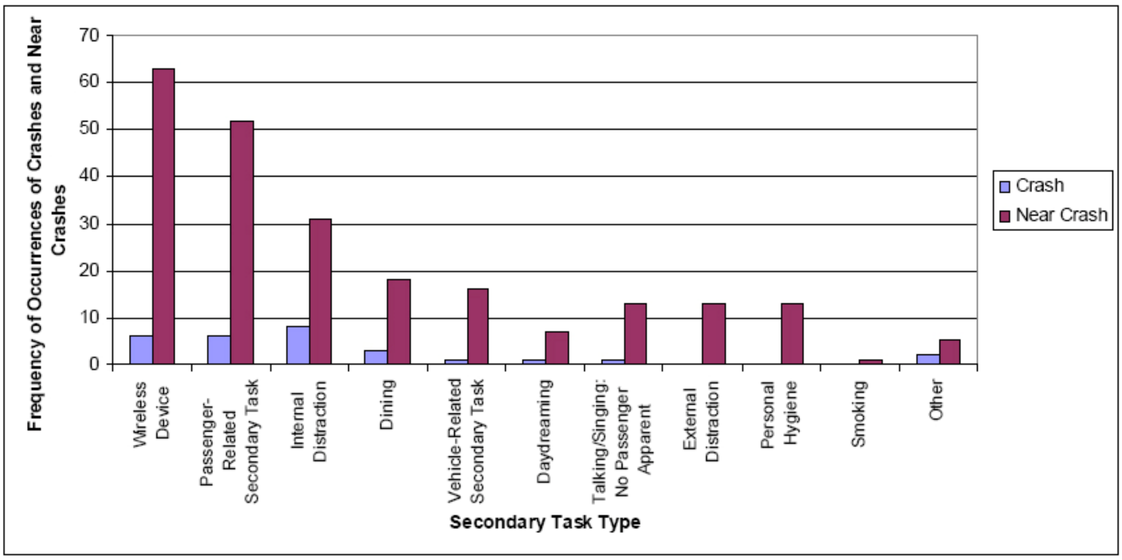


Figure 4. Frequency of occurrence of crashes and near-crashes related to different secondary in-vehicle task types [Dingus et al. 2006].

The results were categorized into four classes of inattention: secondary in-vehicle task engagement, fatigue, driving-related inattention to the forward roadway (e.g. driver checking rearview mirrors or their blind spot) and non-specific eye glance away from the forward roadway (driver glanced away from the roadway, but at no discernable object or person). These four inattention categories contributed to 78% of the crashes and 65% of the near crashes, with secondary in-vehicle task distraction contributing to the most events [Neale et al. 2005]. Figure 4 shows secondary in-vehicle tasks and their frequency of occurrence for crashes and near crashes. The main sources of inattention are wireless devices, passenger-related secondary in-vehicle tasks and internal distraction.

2.5 Guidelines and ISO Norms for Designing Automotive User Interfaces

Interaction principles and design guidelines play an important role in developing user interfaces by standardizing them and making user interaction with them more intuitive. Specific guidelines and ISO norms that address the characteristics of automotive user interfaces exist. In this section, a few guidelines and norms will be introduced.

Different organizations [UN/ECE 1998; JAMA 2004; AAM 2006; European Communities 2007] established recommendations on how to design safe and easy-to-use information and communication systems in the car that make use of visual and audio output. Furthermore, they recommend how to design such systems to be used while driving. All of them aim more or less for the same objectives. As an example, the objectives of [JAMA 2004] should be presented: (1) the system should keep the effect on safe driving to a minimum (2) the visibility of forward field should not be obstructed by the system, that (3) driver's attention should not be distracted from driving and (4) operating the system by the driver should not affect his primary driving task. The guidelines are written for designers of IVISs that are factory-installed but can be partially applied to portable devices [Green et al. 1993; AAM 2006; European Communities 2007].

The recommendations are often divided in different sections discussing the following principles [JAMA 2004; AAM 2006; European Communities 2007]:

1. Overall design principles, e.g. the system must be suitable for the use while driving and interactions must be interruptible so that the driver is able to continue his task after returning his attention back to the interaction with the system

2. Installation principles, e.g. how to position displays and controls
3. Information presentation principles, e.g. only short glances should be needed to spot relevant information
4. Interaction with displays and controls, e.g. at least one hand should remain at the steering wheel
5. System behavior principles, e.g. TV should be automatically be disabled while the vehicle is in motion
6. Information about the system, e.g. the system should have adequate instruction for the driver

Additionally, some guidelines provide specific recommendations for navigation systems and cell phones [Green et al. 1993; AAM 2006] or for messaging and interactive information services like internet searching [AAM 2006]. UMTRI-Guidelines [Green et al. 1993] also include vehicle monitoring guidelines and recommendations for in-vehicle safety advisory and warning systems.

Beside the general guidelines for information and communication systems, there are some more specific guidelines available. The "Design guidelines for safety of in-vehicle information systems" from Stevens et al. [Stevens et al. 2001] deals exclusively with recommendations for information systems that provide the driver with information to his journey, like navigation, congestion or accident warnings. In addition to recommendations for traffic and road information systems, Ross et al. [Ross et al. 1996] make recommendations for collision avoidance und autonomous intelligent cruise control, as well as for road infrastructure systems. There are some specific guidelines for crash avoidance warning devices [Lerner et al. 1996] that include among other things crash warning devices, blind spot warning devices and driver alertness monitoring devices. Campbell et al. [Campbell et al. 1998] provide guidelines for advanced traveler information systems and commercial vehicle operations.

In [SAE 2002; SAE 2004] recommended practices for evaluating the accessibility of navigation systems and route guidance functions while driving. A further method for evaluating a system regarding specific criteria is checklists [Kopf et al. 1999; Stevens et al. 1999; Brook-Carter 2002]. The RESPONSE-checklist [Kopf et al. 1999] is designed for use during the early stages of the system development process and functional specification of driver assistant systems. ADAS QuickCheck [Brook-Carter 2002] takes the "European Statement of Principles on Human Machine Interface for In-Vehicle

Information and Communication Systems" [European Communities 2007] into account and supports the development process in all phases of the product lifecycle: system concept, virtual prototypes, physical prototypes, product on the market and generic products.

Most of the presented guidelines include and refer to international standards that provide fundamental aspects for interaction design in cars. ISO 3958 [ISO 3958:1996] deals with driver's operating distances and describes hand-reach envelopes for passenger cars. The data are applicable for left-hand drive vehicles, as well as for right-hand drive vehicle. Another rather general aspect can be found in ISO 2575 [ISO 2575:2010] regarding the uniformity of symbols for controls, indicators and tell-tales to ensure identification and facilitate use of these devices. Other standards deal with ergonomic design aspects of transport information and control systems (TICS) with respect to visual, auditory and dialogue aspects. ISO 15008 [ISO 15008:2009] describes ergonomical specifications for displays, such as image quality, legibility of characters and color recognition, that contain dynamic visual information. The document also gives recommendations as to which color combinations are useful and how to deal with blinking and image stability. ISO 15006 [ISO 15006:2004] provides ergonomic specifications for the design and installation of auditory displays that present speech and tonal information while driving. It deals with signal specifications, information coding and safety-relevant messages. ISO 15005 [ISO 15005:2002] describes principles for the design process of TICS's dialogue management. Its object is to reduce driver workload and ensure effective and efficient use of TICS.

2.6 Evaluating Automotive User Interfaces

After designing and implementing an automotive user interface according to the described guidelines and principles, it is essential to evaluate its applicability for use while driving. As already mentioned in the introduction, evaluating automotive user interfaces is different from evaluating (graphical) user interfaces in the desktop domain. Automotive user interfaces always have to share driver's attention with the more important primary task of maneuvering the car safely through all kinds of ever-changing traffic situations. For this reason, it is not adequate to only focus on usability and task performance in a non-driving situation.

Burnett [Burnett 2009] summarized three key issues that should be considered by choosing an evaluation method that assesses the safety and usability of automotive user interfaces:

(1) The first issues is the environment in which the method is used, e.g. laboratory, simulator, or on the road. Choosing a suitable evaluation method often implies dealing with the tradeoff between the ability to control the environment and the validity of results. Road tests would, for example, provide the highest degree of realism and therefore deliver highly valid results, but controlling the environment regarding the number and behavior of other cars on the street is nearly impossible; therefore, road tests lack reproducibility and comparability.

(2) The second issue is the occurrence of task manipulation, e.g. single task, multiple task, or no task.

(3) The third issue is which dependant variables need to be measured, e.g. primary task performance data, secondary in-vehicle task performance data, or subjective opinions. The term primary task performance includes all aspects concerning interaction with driving-related vehicle controls. Measures for primary task performance are lateral control (e.g. steering wheel activity, lateral position on the road, or lane deviation), longitudinal control (e.g. speed maintenance or brake pedal activity), car-following performance (e.g. distance to a leading car or time-to-collision), and driver reaction (e.g. recognition time for an unexpected incident) [Bach et al. 2009]. In contrast, secondary in-vehicle task performance denotes all activities related to manipulation of in-vehicle systems while driving. This performance is measured by recording task effectiveness (e.g. interaction errors) and task efficiency (e.g. task completion time or eyes-off-the road time) [Bach et al. 2009]. In the following section, currently-used methods are presented and their advantages and disadvantages are discussed.

2.6.1 Field Trials

In field studies, test cars equipped with operation systems are used. For analyzing driving behavior while interacting with the new system and evaluating the impact of the system on driver distraction, sensors (e.g. cameras) are installed to provide additional data to the CAN (Controller Area Network). With surveys and interviews, drivers' subjective opinions can be collected. Participants drive these cars under real conditions and in most cases for several months.

Kircher [Kircher 2007] summarized possible variants of field studies. The time frame can vary from a single day to several weeks. Participants can but do not have to be informed about data collection. An experimenter can go along with the participants to act as an observer or to give further instructions. Alternatively, the car's data logger can collect data without attracting attention. Field trials can be completely naturalistic or are divided into two parts: a “baseline data collection phase” and the “treatment phase” where the participants are given special instructions. The latest kind of study is called field operational test (FOT).

Field studies are very close to real driving and therefore provide high external validity [Kircher 2007]. However, there are limitations in controlling the environmental conditions, in particular “participants cannot deliberately be exposed to dangerous situations” [Kircher 2007]. Costs of field trials are relatively high and a robust prototype is needed to produce comparable and reliable results; therefore, it is most applicable in late stages of the developing process [Burnett 2009].

Several large-scale field tests have been conducted by the University of Michigan Transportation Research Institute (UMTRI). Typically, around 50 to 100 participants drive instrumented cars for about four to six weeks. One example is the project “Automotive Collision Avoidance System Field Operational Test” [Ervin et al. 2005]. The tested system included an adaptive cruise control, as well as a forward crash warning system. The goal was to research driving safety and driver acceptance of the automotive collision avoidance system. An example of a short-term field trial was carried out by Jensen at al. [Jensen et al. 2010] in Denmark. They conducted a study in real traffic with 30 participants. In four drives with a length of about 16 km, they compared the affect of different output modalities on driving performance.

2.6.2 Test Track Trials

These kinds of trials are short-term studies that are performed on a closed road with an instrumented car. Experimental conditions are more controlled than in a field study, because surrounding traffic can be controlled or is even absent. Because of the controlled environment, driving in more dangerous situations than in field tests can be tested [Kircher 2007]. Variables that can be analyzed are, for example, eye glance behavior, primary task performance data und and subjective preferences. The costs of test track trials are similar to field tests and a robust prototype is required as well.

Disadvantages of test track trials are that participants are more aware of being observed than in field trials, and they are distracted artificially, because waiting until they get distracted “naturally” would take too much time, if it is even possible in the controlled driving situation [Kircher 2007]. Hence, external validity of these studies with respect to distraction is debatable.

In the literature, there are a few test track trials reported. For instance, Ranney et al. [Ranney et al. 2005] compared the effect of interacting with voice-based interfaces versus with visual/manual interfaces on driver distraction. 21 participants drove on a 7.5-mile test track and performed a combination of car following, peripheral target detection and secondary in-vehicle tasks.

2.6.3 Driving Simulators

Driving simulators are effective tools for investigating different user interface with varying degrees of fidelity in a controlled laboratory environment. Time and cost effort highly depends on the kind of simulator that is used. Researchers' demands on the driving simulation can vary considerably. We distinguish between fixed-base and moving-base simulators. A desktop fixed-base driving simulator consists of a screen presenting the driving environment, a gaming steering wheel, pedals and an ordinary chair (e.g. see the RTI's Desktop Driving Simulator in Figure 5 a). In a slightly advanced fixed-base simulator, participants can be seated in a real car or in a mock-up of a vehicle with a significantly larger field of view (e.g. see the National Advanced Driving Simulator MiniSim^{TM} in Figure 5 b). However, an exact categorization of fixed-base driving simulators is difficult, because the differences in their setups are very subtle. What all fixed-base simulators have in common is that they are inexpensive to build, maintain and use. Moving-base driving simulators enhance the driving simulation by providing acceleration cues to the driver. Moving-base simulator configurations range from simple moving driver seats (e.g. see Figure 5 c) to cabs with a mock-up of a vehicle that are moved in all directions within a large interior of space (e.g. see The National Advanced Driving Simulator in Figure 5 d).

Driving simulators have both benefits and disadvantages over field trials and test track trials. The following issues mainly based on [Evans 2004; Burnett 2008]. The benefits are a risk-free simulation of potential dangerous situations, a controlled environment that enables any number of exact comparable and reproducible experiments, less space required compared to test tracks, irrelevance of environmental conditions like weather and lighting on the experimental design, and more robust data recording compared to road trials since there are no complex sensors needed.

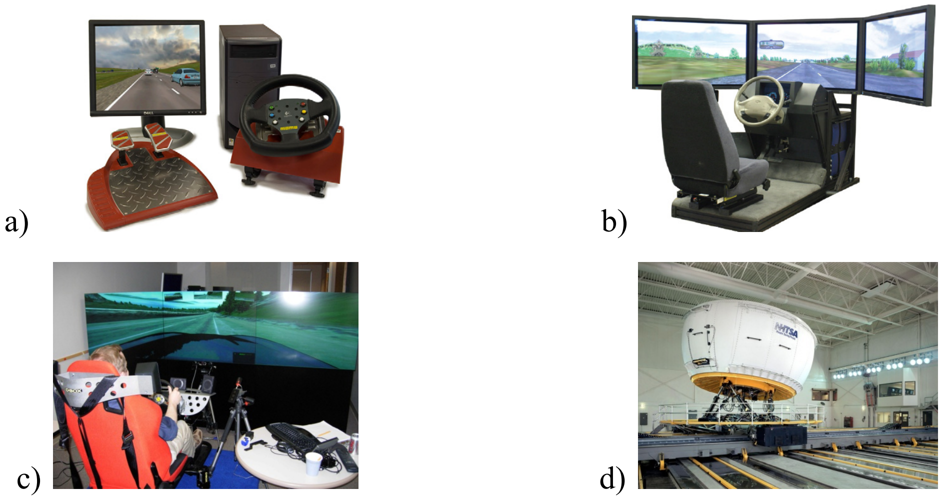


Figure 5. Different driving simulator setups. Fixed-base simulators: a) RTI's Desktop Driving Simulator [@RealtimeTechnologies] and b) NADS MiniSimTM [@NADS(2)]. Moving-base Simulators: c) Mitsubishi Electric Research Labs' Low cost Driving Simulator [Weinberg, Harsham 2009] and d)The National Advanced Driving Simulator [@NADS(1)]

On the other hand there are a few disadvantages or problems with driving simulators. One main issue is that individuals can experience symptoms of simulator sickness, e.g. nausea, dizziness and headaches, that often lead to failed experiments. Barrett provide a good survey of this phenomenon [Barrett 2004]. The second main issue is the validity, particularly behavioral or construct validity. To what extent do drivers behave in a simulator as they would in the real world? Studies have been conducted to try and show the validity of simulator experiments. For an overview, see [Blana 1996; Hoskins, El-Gindy 2006]. Blana [Blana 1996] concludes in her literature review that there are differences between the real and the simulated environment independent of whether the driving simulator is low-cost, medium-cost or high-cost. A carefully designed experiment seems to be the most important element. Regarding fixed-base and moving-base driving simulators, she didn't find enough evidence that moving-base driving simulators are better than their fixed-base counterparts. These validation studies are not without controversy. For example, Burnett [Burnett 2008] raises concerns that existing studies tend to be very specific so that it is difficult to generalize from their results. Furthermore, he complains that authors have only examined a small number of variables and do not report critical data regarding the configuration. Probably, the validity of driving simulator studies will remain a topic for discussion and the basis for further research activities. One step towards greater comparability between driving simulator studies has been the introduction of the Lane Change Test (LCT), which will be presented in the next section.

2.6.4 Accessing Driving Performance – Lane Change Test

The Lane Change Test (LCT) is an easy-to-implement and low-cost assessment methodology [Mattes 2003; Mattes, Hallén 2008]. Since its creation, it has received a lot of attention and appears to be a practical, effective and standardized tool that addresses the need for comparable driving simulation experiments. LCT was a product of the ADAM (Advanced Driver Attention Metrics) project and recently became a standardized ISO tool [ISO 26022:2010]. LCT offers a means for quantitatively measuring human performance with a simple driving task while performing a secondary in-vehicle task concurrently. An estimation of the secondary in-vehicle task demand is the result. LCT was designed to be used by Original Equipment Manufacturer (OEM), in-vehicle device manufactures, universities and other organizations.

Drivers perform a secondary in-vehicle task while driving in a simulated driving environment. Experimental setup is characterized by its competitive equipment. In the most minimalist setup, participants are seated on a normal chair in front of a screen (with a minimal resolution of 1024x768 and a color depth of 24 bits) and a small game steering wheel with foot pedals (see Figure 6). Opportunities for using LCT in combination with a driving simulator or in a real car are also described in [ISO 26022:2010].

Participants are requested to repeatedly perform lane changes on a straight three-lane road as soon as they are indicated by signs appearing on both sides of the road (see Figure 7). While not actively changing lanes, the user is requested to stay within the current lane as precisely as possible. There is no other traffic on the road. The track is about 3000m long and the distance between lane-changing signs varies between 140 and 180 meters. Blank signs are always visible, but lane change instructions appear first when the user is within 40 meters. The drivers are instructed to press the gas pedal to the floor, so that they drive at a constant speed of 60km/h. At this speed, the duration of a track is 180 seconds. The constant speed uniforms driving demands and comparable driving performance measurements, i.e. the mean deviation of the lane between a normative model and the actual driving along the track. The result is a single value that indicates a combination of the driver's awareness of the driving environment (including perception and reaction to lane changing instructions) and their ability to safely maneuver the vehicle and stay in the lane. The simulated driving task resembles the visual, cognitive and motor demands of driving.

Figure 6. LCT setup consisting of a screen showing LCT driving environment and a gaming steering wheel.

Figure 7. LCT driving environment with signs requesting a lane change from the middle lane to the left lane.

A typical experiment comparing two secondary in-vehicle tasks has the following driving procedure: about 3 minutes in a test round, then 3 minutes without any secondary in-vehicle task to record a baseline driving performance, 3 minutes with the first secondary in-vehicle task, 3 minutes with second secondary in-vehicle task and finally 3 minutes for a second baseline to control the learning effects. For analysis, the position in the lane is recorded. A simple model is used to assess driving performance (see Figure 8). Blue areas in Figure 9 indicate driving quality and are sensitive to perception, reaction, maneuvering and lane keeping. The average value of baseline drives, as well as the average of each secondary in-vehicle task drive, is calculated. The deviation value for each secondary in-vehicle task is divided by the deviation value of the baselines to get a measure of relative decrease in performance. The result is called fraction:

$$fraction = \frac{\text{mean deviation while driving with secondary in−vehicle task}}{\text{mean deviation while driving without secondary in−vehicle task}}$$

The mean deviation values can be compared statistically with typical methods of statistical inference (e.g. t-Test or ANOVA).

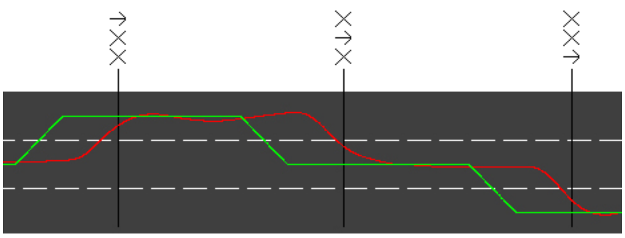


Figure 8. Comparison of driving data (red line) and normative model (green line).

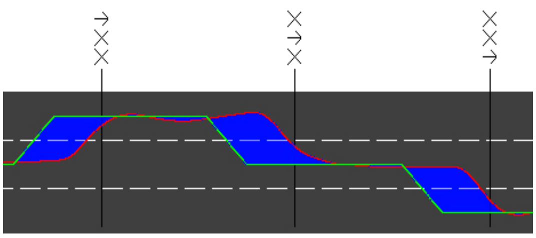


Figure 9. Blue areas indicating driving performance.

The main benefit of LCT is that it provides quantitative results and is a replicable measurement method that is useful in most stages of the development process of automotive user interfaces. Results of a first experiment with LCT reported in [Mattes 2003] show that LCT is able to find significant differences among twelve in-vehicle tasks, and the results also correlate with results of a high-end moving-base driving simulator. Performed in-vehicle tasks were: talking on telephone, unwrapping a sweet, unfolding a Kleenex and putting it on the passenger seat, entering a street name with a rotary push button and onscreen keyboard, entering a 4-digit pin in a cellular phone, etc. Experts might have already expected some of the tasks to be distracting, but with LCT an objective value could confirm their expectations and allow the distraction level of in-vehicle tasks to be compared.

Mattes [Mattes 2003] also mentioned the main limitation of the LCT: it can only be used to evaluate secondary in-vehicle tasks that are compatible with its procedure. Thus, tasks such as lane keeping guidance, reaction to navigation instructions or those requiring speed variations could not be tested. Another important aspect is addressed in [ISO 26022:2010]: “The interpretation of LCT performance measures depends upon the way that participants allocate attention between the primary task and the secondary task[1] they are performing at the same time.” Even with the same instruction, some participants may allocate more attention to the primary task while others allocate more attention to the secondary in-vehicle tasks. This variation in attention allocation may lead to differences in driving performance, as well as in task performance. Therefore, it is essential to also consider secondary in-vehicle task performance, specifically task completion time and performed errors. When comparing in-vehicle tasks with LCT, [ISO 26022:2010] suggests finding a single index that combines degradation on both LCT and secondary in-vehicle task performance. The need to analyze secondary in-vehicle task performance is also emphasized by other researchers [Harbluk et al. 2009; Mitsopoulos-Rubens et al. 2010].

Since LCT was in the process of becoming an ISO standard, there are some studies performed addressing the validity and reliability of LCT. Some of the results provide evidence that LCT is an effective measure of driver distraction [Burns et al. 2005; Harbluk et al. 2007]. Beside validity and reliability, LCT’s sensitivity plays an important role. In the best case scenario, it would be sensitive to small variations of in-vehicle tasks and could therefore demonstrate that one task is significantly more suitable while driving than the other. For example, it would be able to prove that

[1] In our terminology that is referred to as “secondary in-vehicle task“.

interacting with navigation system A is less distracting than interacting with navigation system B. This issue is addressed by Young et al. [Young et al. 2010]. They performed an experiment with visual-manual and cognitive surrogate IVIS tasks with different levels of demand. One of their key findings was "The mean deviation and lane excursion measures were able to distinguish between the visual and cognitive tasks, but were less sensitive to the different levels of task demand", and they suggest further refinement of the LCT's metrics for increasing its utility. Bruyas et al. [Bruyas et al. 2008] focused on "Consistency and sensitivity of lane change test according to driving simulator characteristics". They compared the use of LCT in a driving simulator condition with a minimalistic setup consisting of a 17"screen and a gaming steering wheel. The results showed that mean deviation in the simulator condition was smaller, and the ratio of correct lane changes was higher than in the PC condition. In contrast, participants reacted quicker to signs when using the PC. They concluded that the "LCT was also proved to be sensitive enough to evaluate driving performance impairment because of the simultaneous performance of secondary tasks[2], even if it failed to differentiate all of them."

Petzoldt et al. [Petzoldt et al. 2009; Petzoldt et al. 2010] investigated gender and training effects of LCT. An experiment regarding gender effects on lane change test performance showed that men are better "lane-changers" than women. Therefore, they suggest that it is important to balance subject samples for gender to assure comparability of LCT results [Petzoldt et al. 2009]. Results of two other experiments indicate that "participants performance improves significantly after just one LCT encounter, and that this improvement is rather stable" [Petzoldt et al. 2010]. The validity of LCT results might be threatened by this training effect; therefore, they recommend performing experiments with only "novice participants" or "expert participants". Both approaches seem to be useful, because they reflect different use cases – "first encounter" vs. "everyday usage".

LCT provides also a basis for further development. For example, Spießl and Mangold [Spiessl, Mangold 2010] developed Autonomous Lane Change Test (ALCT), a variation of the LCT for evaluating the influence of secondary in-vehicle tasks during automated driving. The car performs lane changes automatically but with an error rate of 10%. Thus, instead of measuring driving performance, they measure response time, missed errors and false reactions as indications of distraction imposed by secondary in-vehicle tasks.

[2] In our terminology that is referred to as "secondary in-vehicle tasks".

In conclusion, LCT is a standardized method for evaluating automotive user interfaces regarding driver distraction. Initial experiments show evidence that it might be a right step towards a comparable evaluation method, but further research is needed to evolve it into the valid and reliable tool that was intended by its developers in the early stages.

2.6.5 Occlusion Test

Occlusion test is a laboratory-based method that focuses on the visual demand of in-vehicle systems [ISO 16673:2007]. The assumption is that glance behavior while performing an in-vehicle task can be simulated by allowing participants only brief periods of vision. Participants wear computer-controlled goggles with LCDs as lenses that can be opened and shut in a precise manner. The closing and opening of the lenses simulate successive glances between road and information systems. A vision period of 1.5 seconds follows an occlusion period of 2 seconds. In that time, vision is obscured to simulate the glances at the road scene. Participants perform in-vehicle tasks on a desk or in a parked car (see Figure 10). Task performance, error rate, task completion time and ease of resumption after interruption are measured and evaluated [Young et al. 2003]. Tasks that are effectively performed with a series of short glances can be considered suitable for being carried out while the car is in motion, because they seem relatively easy to resume [Stevens et al. 2004].

Figure 10. Participant wears occlusion goggles with shutters open (left) and closed (right) [Pettitt et al. 2006a].

The ISO standard on the occlusion technique [ISO 16673:2007] gives guidance on how many participants are required for a study, how much training to give, how many trials with full vision vs. intermittently-occluded vision to perform, and how to analyze data. Two key metrics are proposed: the total shutter open time (TSOT), the total time participants had vision while performing the task, and the resumability ratio (R), the ratio of TSOT to task time when participants perform the task without visual restrictions.

Compared to road or simulator studies, the occlusion technique is rather low cost and easy to implement. Nevertheless, it requires a robust prototype that limits its usage in early stages of the design process [Pettitt et al. 2006a]. Just as with driving simulation studies, discussion about validity of the occlusion technique arises. Pettitt et al. [Pettitt et al. 2006a] provide an overview of conducted studies and reports on his own research. They compared results of an on-road evaluation with results gained through the occlusion method and found out that “trends predicted by occlusion were mirrored in the results from the on-road study” [Pettitt et al. 2006a].

2.6.6 Peripheral Detection Task

The peripheral detection task (PDT) is a method for measuring driver’s mental workload and visual demand. Participants have to react to a visual stimulus presented at the periphery of their field of view. Generally, small red lights are illuminated for 1-2 seconds with varying intervals of 3-6 seconds in an angle that is between 5° and 25° left of the driver’s field of view [Jahn et al. 2005]. While performing an in-vehicle task, participants have to respond to this stimulus by pressing a micro switch that is attached to the index or middle finger of the dominant hand as soon as possible. Reaction time and hit rate are measured as indicators of the attentional demands of the environment [Kircher 2007].

PDT was first described by van Winsum, Martens and Herland [Van Winsum et al. 1999]. Initially, it was used to measure driver mental workload and attentional demands of driving itself. However, several driving studies (e.g. [Harms, Patten 2003; Jahn et al. 2005]) and simulator studies (e.g. [Burns et al. 2000]) demonstrated the usefulness of PDT to measure the level of distraction afforded by in-vehicle systems as well.

The advantages of this method are good experimental control, large quantity of data that one can collect within a short time period and with high reliability [ISO 26022:2010]. PDT assesses cognitive demand, as well as visual demand [Burnett 2008]. The major drawback of this method is that it has very low realism [ISO 26022:2010]. Further disadvantages are that it is not fully standardized. Therefore, the ability to perform cross-study comparisons is limited [Burnett 2008]. Furthermore, it is “difficult to discern between the level of cognitive demand and the visual demand for a given user interface” [Young et al. 2003]. Engstrom, Aberg and Johannsson [Engström et al. 2005] address this last issue by introducing a haptic peripheral detection task to provide a means for measuring only the cognitive load. In their task, participants respond to a vibro-tactile stimulation at the wrist.

2.6.7 Measuring the User

The above presented methods mainly focus on measuring primary task performance and secondary in-vehicle task performance. Furthermore, measurements taken from the driver can provide information on to what extent a new automotive user interface affects the driver's attention. Physiological measurements and eye glance behavior can be collected directly during the experimental runs, and self-reported measurements (provided through questionnaires) can be taken before and after each experimental run.

Physiological Measure

Variations in physiological parameters are considered to be indicators that the driver's internal condition reflects his workload [De Waard 1996]. On this account, physiological measurements are used in simulated or real driving studies to monitor the driver's physical state continuously and, due to miniaturization of such monitoring equipment, more or less unobtrusively. The most commonly used measure is the heart rate, which is measured with an electrocardiogram. A few studies show the validity of this method for measuring driver workload, e.g. [De Waard, Brookhuis 1997; Richter et al. 1998], even though heart rate is not able to measure workload over short time periods. It reacts slowly and needs a while to return to starting basis.

Galvanic skin response is another physiological parameter that reacts fast on emotional load. [Helander 1978] showed its applicability for researching the driver's workload. Further physiological measurements are respiration, electromyogram (e.g. muscle contraction), body temperature, blood pressure variability and skin conductance [Green 1995; Bach et al. 2009]. Physiological parameters influence one another, e.g. respiration affects ECG data. Therefore, it is recommended to collect different physiological parameters in order to interpret the data in a feasible manner.

Eye Glance Behavior

Another measurement that can be taken from the user without his active help is his eye glance behavior. By observing eye glances, the impact of interacting with an IVIS display on visual attention can be quantified. Victor et al. [Victor et al. 2005] describe a glance as a "transition to a given area, such as a display, and one or more consecutive fixations on the display until the eyes are moved to a new location." Drivers usually complete a secondary in-vehicle task while driving through a series of 1-to-2-second glances at the object. The driver's glances alternate between the object and the roadway.

Usually, glances at a particular object are recorded and analyzed regarding eye glance frequency and eye glance duration, which give a measure of the total "eyes of the road time" [Fairclough et al. 1993]). Total eyes-off-road time is a commonly used and valid measure of visual demand while being engaged in secondary in-vehicle tasks [Young et al. 2003]. Correlation between eye glance measures, total task duration and lane-keeping measures can be seen as generally high [Green 1999b].

Eye glance behavior can be measured by videotaping the driver's eyes. However, frame-by-frame analysis of these data is a very time-consuming process. To simplify this process, sophisticated eye tracking devices can be used that allow real-time measurement of glance frequency and duration. These devices are, however, still rather expensive.

Subjective Assessments

Subjective ratings of workload are used to discover participants' perceptions of attention capacity before, during and after a user study. There are a number of workload rating methods described in research literature. In the remainder of this section, NASA-TLX (NASA task load index) and DALI (Driving Activity Load Index) will be presented briefly, as they are often used in studies in the driving context.

NASA-TLX [Hart, Staveland 1988], originally created by NASA for evaluating a pilot's workload, is a multi-dimensional rating procedure that consists of six component scales, each ranging from low to high:

1. Mental Demands – includes thinking, deciding, remembering, etc.
2. Physical Demands – includes turning, pulling, pushing, controlling, etc.
3. Temporal Demands
4. Performance
5. Effort – includes mental and physical work
6. Frustration – ranges from discouraged/irritated/stressed to secure/gratified/relaxed

After rating each of these six components, participants are presented the factors in pairs (all possible combinations) and asked to decide which of the two factors is more relevant to their personal definition of workload for the given task. Weights are derived from this rating and multiplied by the component scales rating provided by that participant during the study. The weighted average of the six factors provides an overall workload score. The advantage of this weighted workload score is "an increase sensitivity (to relevant variables) and a decrease in between-rater variability" [Hart 2006]. Figure 11 illustrates an example of a filled-in NASA-TLX questionnaire including mean workload calculation.

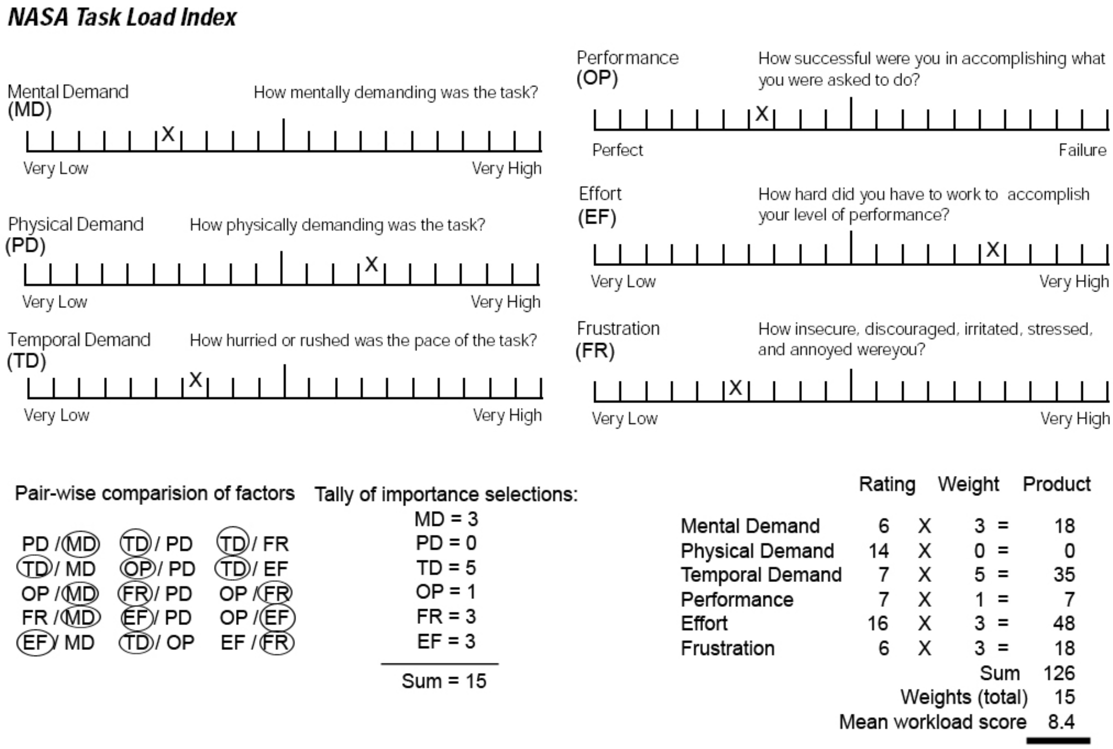


Figure 11. NASA Task Load Index illustrated on an example including mean workload calculation [@humansystems].

DALI [Pauzié, Pachiaudi 1997; Pauzié 2008b] is a variant of NASA TLX that is adapted to driving activity. It is especially used to evaluate driver workload generated by automotive user interfaces during a well-defined driving task. DALI addresses various components of driving task workload: perceptual load, mental workload and the driver’s state.

These components are sub-divided into specific factors:

- Perceptual load: Visual demand, auditory demand and tactile demand
- Mental workload: Attention effort (e.g. to think about, to decide, or to choose), temporal demand (specific constraint felt due to time constraints when running the activity) and interference (disruption induced by system use and drive at the same time)
- The driver’s state: Situation stress (e.g. tiredness, insecurity, or irritation)

Like in the NASA-TLX questionnaire, participants rate these factors on a scale ranging from 0 (low) to 5 (high) with regard to their usual driving activity. The scale rating procedure followed a weighted procedure in order to combine the six dimensions into a global score. Experimenter can suppress any factors that are not important for evaluation in a specific experiment. For example, there is no need to evaluate "tactile demand" when there is no vibration in the experiment.

Pauzié [Pauzié 2008a] highlighted the main advantage of DALI as "it makes it possible to identify the origins of driver workload, allowing for corrective action at the identified level (e.g. high interference and visual load will indicate that an in-vehicle system has a demanding visual display)."

2.6.8 Non-user-based Measures

All aforementioned methods require a user to perform specific tasks. However, user trials are often time consuming and come too late in a design process to be of considerable benefit. Checking an existing system or design sketch against international standards and guidelines as an expert review is one non-user-based method that should be only mentioned at this point because an overview of commonly used checklists can be found in chapter 2.5. In this section, the focus should lay on anticipating and predicting human behavior to model interaction with user interfaces or software. The most-used modeling technique in the area of HCI was presented by Card, Moran and Newell in 1983 [Card et al. 1983], and it's called GOMS. A description of its components, along with an example of each in the driving context, can be found in Table 1.

	Description	**Example (driving context)**
Goal	What the user wants to achieve by using this system	Playing a specific song from a list of songs.
Operators	Actions that the system allows the user to take to achieve the goal	Scrolling through a list with a multifunctional controller, pressing a button, speaking a voice command, etc.
Methods	Sub-goals and operators necessary to accomplish a goal	a) Selecting the menu item "music" by rotating the multifunctional controller, scrolling through a list of songs, pressing a button to play a selected song b) Pressing the push-to-talk button, saying "Play" and then the name of the song
Selection rules	Which method the user prefers to achieve the goal	Using method a) or b)

Table 1. Description of GOMS's components each with an example from the driving context.

The main benefit of GOMS is to provide designers and system engineers with quantitative and qualitative predictions of a user's behavior [John 1995]. GOMS does not deal with problem solving issues; instead, it addresses expert users. It provides information about the predicted execution time, how long the learning period for the task will be, human costs of the system, and costs from possible errors [John 1995]. It is well suited to evaluate early design ideas, because no working prototype is needed.

GOMS, in its original form, allows modeling a single task sequence, and therefore, it is rather inappropriate in the driving context. Urbas and Leuchter [Urbas, Leuchter 2008] expanded GOMS by including the multitasking characteristic of the driving task – driving and concurrently interacting with an IVIS. They called it Multi-Tasking GOMS. Their approach consists of three main components:

- Resource Profile: Represents the driver's workload in a typical traffic situation, including cognitive, visual, auditive and manual resources
- Task Model: Analysis of secondary in-vehicle tasks according to GOMS notation with specific multitasking extensions
- Interference Engine: Combination of primary and secondary in-vehicle task descriptions and generation of an integrated multitasking model

The authors stated that "Multi-Tasking GOMS and the implementation mtGOMS are valid and useful to improve the usability engineering processes in IVIS development" [Urbas, Leuchter 2008].

The simplest model of the so-called GOMS family is the keystroke-level model (KLM) introduced by Card, Moran and Newell [Card et al. 1980]. Its goal is to predict how long it takes an expert user to perform a specific task on a specific computer system. Keystrokes and other low-level operations are counted, and their assigned task times are summed up to one single time value. KLM is especially useful for comparing different sequences of operators that led to the same goal. The original form of KLM divides a complex task into six operators: keystroke or button press (e.g. 0.20 sec for an average skilled typist), pointing to a target with a mouse (1.10 sec), homing the hand on the keyboard or other device (0.40 sec), drawing straight-line segments (time depends on their lengths), mental operator (1.35 sec) and response time by the system (time depends on system). The mental operator requires special treatment, because not all actions involve the user thinking about the next move. Card and Moran provided specific placement rules for this operator.

In the literature, some studies that apply the KLM techniques to the driving context can be found. Manes et al. [Manes et al. 1997] introduced typical times for operators for navigation data entry. In a user study comparing KLM times with times recorded through a driving simulation experiment, they found strong correlations between observed and predicted times. A similar result could be found in an in-car entertainment study produced by Stanton and Young [Stanton, Young 2003]. Green [Green 1999a] proposed a combination of the 15-second rule and KLM. The 15-second rule is defined by the Society for Automotive Engineers (SAE), which states that a navigation-related task that takes longer than 15 seconds in a stationary condition should not be allowed in a moving vehicle [SAE 2004]. Green introduced vehicle-specific operators like "reach near operator" (e.g. reaching from the steering wheel to other parts of the wheel, stalks or pods) or "reach far operator" (e.g. reaching from steering wheel to center stack).

These new homing operators are researched further by Pettitt et al. [Pettitt et al. 2006b]. They divided the homing operator into three subclasses: homing from the steering wheel to the IVIS, homing from the IVIS to the steering wheel and homing between controls on the IVIS. Fitt's law was used to determine the times for each homing operator. Pettitt et al. reported about the debate regarding the practicability of measuring static task times of in-vehicle devices [Pettitt et al. 2006b]. They claimed that the multitasking aspect – driving and interacting with the IVIS – has to be assessed by KLM too. In another study, Pettitt and colleagues [Pettitt et al. 2006a] addressed this issue and extended KLM by prediction measures based on the occlusion method. Their study focused therefore on visual demand. They added vision/no-vision intervals of 1.5 seconds, according to specific assumptions that they had made, to the interaction sequence and predicted a total task time under occluded conditions. A high correlation between predicted and observed values gained through the occlusion method could be also found in this study, and it seems that the extended KLM has potential as a low-cost evaluation method that can be used in early stages of the design process. However, the authors still see room for further development, especially regarding introducing new operators and the improving the reliability of their technique.

Another approach for modeling user behavior is given by ACT-R (adaptive control of thought, rational) [Anderson 1993]. ACT-R is a cognitive architecture that helps to simulate and understand human cognition. Salvucci [Salvucci 2006] integrates driver modeling in the ACT-R architecture. His driver model, comprised of basic driving maneuvers such as lane changing, is integrated with models of secondary in-vehicle task behavior to predict driver distraction. Salvucci's Distract-R system [Salvucci 2009], which will be explained in more detail in chapter 6.1.2, allows users with little knowledge of cognitive modeling to assess these models for evaluating automotive user interfaces. Distract-R seems to be an interesting tool for in-vehicle research. However, independent validation of the system is still needed to judge its outcome regarding driver distraction.

2.7 Internal References to further Related Work

Related work for the specific topics in this dissertation can be found directly in the corresponding chapters. Thus, chapter 3.1 provides related work on design spaces for user interfaces, chapter 4.2 offers related work on tactile output and handwriting opportunities in the car, chapter 5.1 presents related work on implicit interaction in the car and gaze tracking, and chapter 6.1 includes related work on how the continued development of automotive user interfaces can be supported.

3 Design Space

A vast number of different car models are being driven worldwide. One thing that all of these cars have in common is that controls for primary tasks are mounted at the same positions, even in left-hand drive and right-hand drive vehicles. Nowadays, if a driver sits in a typical passenger car, he will find a steering wheel in front of him and two or three pedals, depending on whether the transmission is automatic or manual, on the floor at a reachable distance. This setup guarantees that anyone with a driving license can perform the primary task – driving the car. Devices for the secondary in-vehicle tasks are also similarly arranged in different models and brands of cars. In contrast, user interfaces for tertiary tasks differ greatly with regard to the number of input and output devices and their placement in the car. Many manufacturers combine a large number of infotainment and entertainment functionalities into one system, which consists usually of a multifunctional controller and a high resolution display, e.g. the Audi MMI system [@Audi (1)] or the BMW iDrive [@BMW].

In this chapter, we present a design space for driver-based automotive user interfaces. Most of the parts described in this chapter have been published at the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI 2009) [Kern, Schmidt 2009].

The design space provides an overview of input and output devices in cars with respect to their placement, which part of the body they interact with and which kind of feedback they provide. Taking into consideration that there are already research efforts for replacing the steering wheel by a joystick, e.g. [Kienle et al. 2009], which may eventually change the arrangement of devices for the primary tasks, we decided to concentrate on a design space that includes devices for primary, secondary and tertiary tasks. This design space is intended to provide a common basis for analyzing and discussing different user interface arrangements in cars, to compare alternative user interface setups, and to identify new opportunities for interaction and placement of controls. We focus on user interfaces that are operated by the driver, but the proposed design space can be extended to include passenger-controlled user interfaces.

We also provide a visual representation of the design space that allows the designer to see potential problems with their designs, e.g. adding a new control that occupies the same region in the design space as existing controls may interfere with their functionality. The following assumptions and statements refer to left-hand drive vehicles, but they can be easily applied to right-hand drive vehicles by substituting “left” for all occurrences of “right” and “right” for “left”.

This chapter starts with a description of related work on design spaces for user interfaces. An examination of the design space followed, including an inspection of different input/output devices and different parts in the car where the devices can be placed. After introducing the graphical representation, a few examples are presented to illustrate the use of the design space. A discussion about the suitability of the design space completes this chapter.

3.1 Related Work on Design Spaces for User Interfaces

The importance of understanding design spaces for user interfaces is emphasized by HCI researchers. However, it is difficult to find a common definition of the term "design space". Ballagas et al. address this issue by providing a key term explanation:

> *"Design spaces provide a formal or semiformal way of describing and classifying entities along different dimensions, each listing relevant categories or criteria." [Ballagas et al. 2008]*

To visualize a design space, a graphical representation is often provided. In this section, different design spaces and taxonomies for user interfaces and their graphical representations are presented.

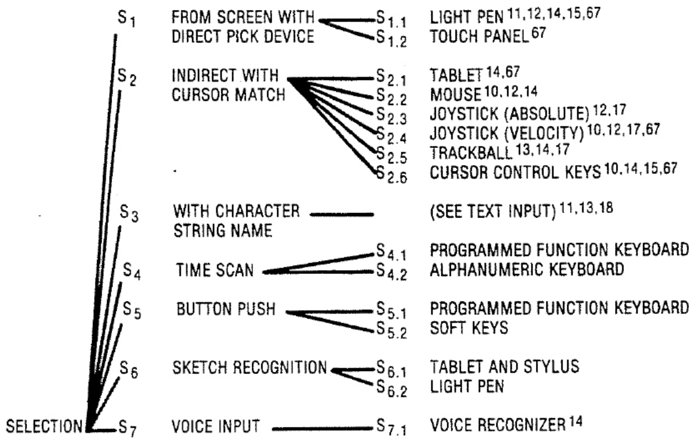


Figure 12. Foley, Wallace and Chan's graphical representation of the assignment of input devices to the graphical subtask selection [Foley et al. 1984].

The classic paper from Foley, Wallace and Chan [Foley et al. 1984] provides an early taxonomy of input devices and can be seen as a first step for analyzing the design space of such devices. They classified desktop input devices by the graphical subtask that could be performed with them. The subtasks are Position, Orient, Select, Path, Quantify and Text Entry. For example, a light pen is capable of selecting an item directly from the screen or a mouse controls the position of a cursor indirectly on the screen. For each subtask, a visual treelike diagram is introduced (see Figure 12).

Around the same time, Buxton published a paper about "Lexical and Pragmatic Considerations of Input Structure" [Buxton 1983]. He introduced a taxonomy of hand-controlled continuous input devices and organized them in a two-dimensional table (see Figure 13). The rows delimit the physical properties (what is being sensed), i.e. position, motion and pressure, and the columns delimit the number of spatial dimensions being sensed, i.e. 1, 2 and 3. Subdivisions allow similar devices to be grouped and transducers to be differentiated by whether they sense potential via mechanical or touch-sensitive means. The table is useful to find appropriate equivalences and in helping quantify the generality of various physical devices.

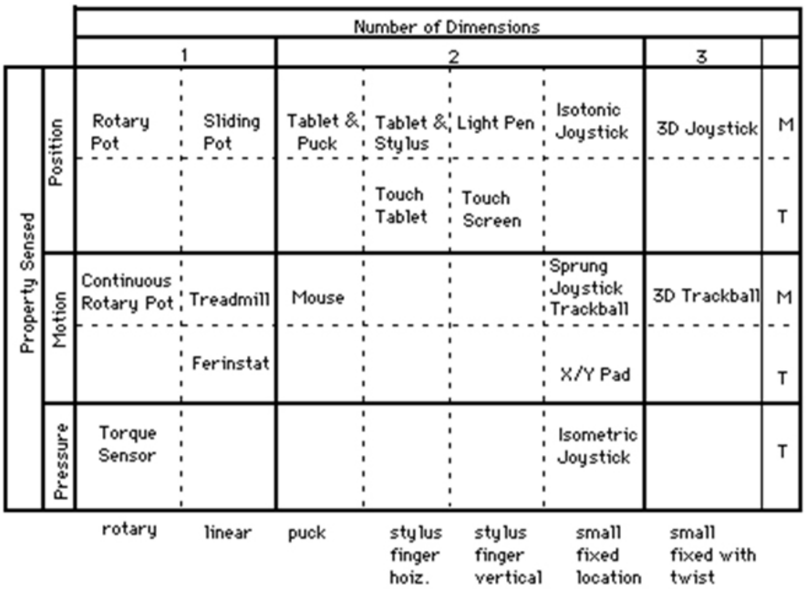


Figure 13. Buxton's tableau of continuous input devices [Buxton 1983].

Card et al. addressed the limitations of Foley et al.'s classification ("the categories, while reasonable, are somewhat ad hoc and there is no attempt at defining a notion of completeness for the design space.") and Buxton's taxonomy ("it only includes continuous devices") by providing their own design space for input devices [Card et al. 1990].

They built a taxonomy of input devices that allows the semantic of a device to be described and its expressiveness to be measured. For modeling the language of input device interaction, they use a primitive movement vocabulary and a set of composition operators. The input device is represented by a six-tuple (M=manipulation operator, In=input domain, S=current state of the device, R=Resolution function, Out=output domain, W=additional device properties), and they distinguish between three composition operators – merge, layout and connect – for combining the vocabulary. For example, the mouse consists of two orthogonal one-dimensional sliders (merge composition). These XY sensors and the three buttons form the mouse (layout composition). The mouse's output is connected to the input for the screen cursor (connect composition). They define the design space for input devices as "the set of possible combinations of the composition operators with the primitive vocabulary" [Card et al. 1990]. Figure 14 shows their graphical visualization based on the physical properties used by input devices (Position P, Rotation R, Movement dP, Delta rotation dR, Force F, Torque T, Relative Delta force dF, Delta torque dT), taking the mouse as an example. This visualization can be used to classify nearly all existing devices and to generate ideas for new devices.

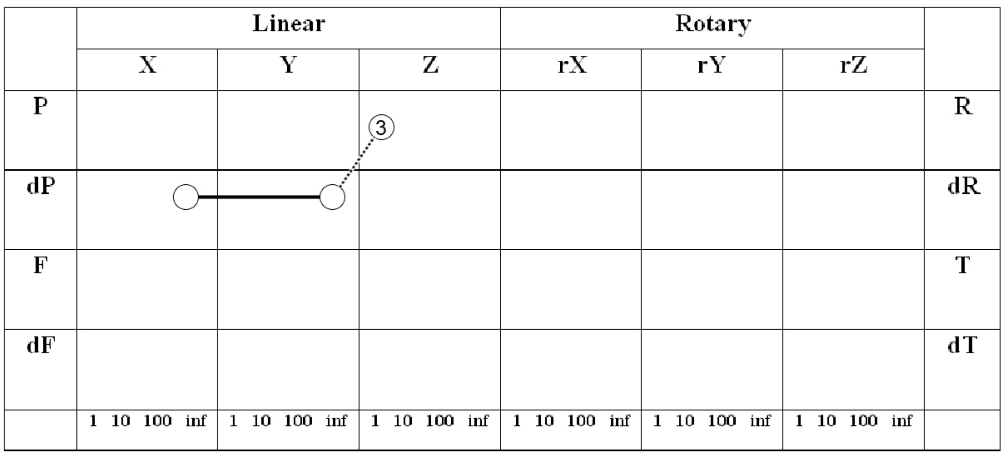


Figure 14. Graphical representation of Card et al.'s input device taxonomy. As an example, the design space of a mouse is illustrated. The circles indicate that the mouse sense linear movement along the X and Y axes, as well as 3 positions on the Z-axis (3 buttons). Nearly continuous resolution is indicated by the placement of the X and Y circles to the right of the column. The location of the button circles to the left indicates controls with only two states. The merge composition between the X and Y component is represented by a black line, and the layout composition between X and Y components and the three buttons is represented by a dashed line. According to [Card et al. 1991].

With the upcoming trend of ubiquitous computing [Weiser 1995] and the request to use alternative input and output modalities for communicating with computers, design spaces and taxonomies for more specific areas of user interfaces have been examined, e.g. tangible interfaces [Fishkin 2004], virtual reality interfaces [Coomans, Timmermans 1997], tactile input technologies [Hinckley, Sinclair 1999], wearable computing [Gemperle et al. 1998] and ambient information systems [Pousman, Stasko 2006].

As one example for this new kind of design space, Ballagas et al.'s analysis of the design space of ubiquitous mobile input [Ballagas et al. 2008] will be described in more detail. They considered the mobile phone to be the first truly pervasive computer and therefore analyzed input and output capabilities for modern mobile phones. These capabilities range from keypads over displays to connectivity via UMTS. All these input and output capabilities not only provide means for keeping in touch with others but also enable the user to interact with the physical world. Using the taxonomy from Foley, Wallace and Chan [Foley et al. 1984] for desktop input devices, which is described earlier in this work, they analyzed recent mobile input techniques for ubiquitous computing application scenarios and defined the design space. Their analysis builds on the classic design spaces from Buxton [Buxton 1983] and Card et al. [Card et al. 1991], as well as their own previous work on the design space of input techniques [Ballagas et al. 2006]. In Figure 15, their graphical representation of the design space and the results of the analysis are shown.

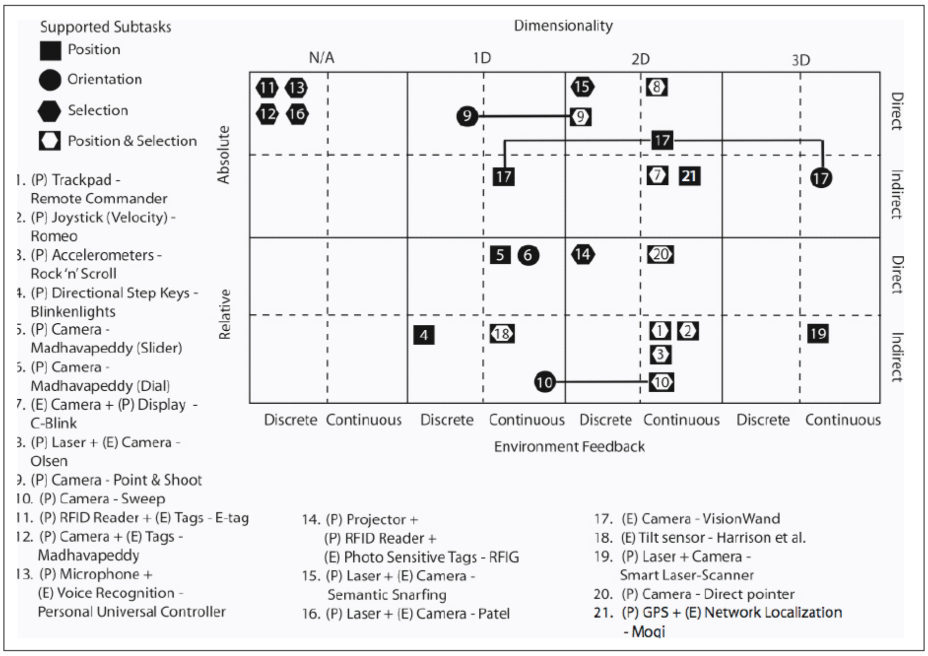


Figure 15. Graphical representation of the design space ubiquitous mobile input - Classification of different mobile phone interactions [Ballagas et al. 2008].

Ballagas et al. [Ballagas et al. 2008] propose a five-part spatial classification for ubiquitous mobile phone interaction tasks that consists of supported subtasks (position, orientation, selection), dimensionality, relative vs. absolute, interaction style (direct vs. indirect), and feedback from the environment (continuous vs. discrete). The design space and its visual representation should help to identify relationships between input techniques, to identify gaps, and to predict future interaction techniques.

A design space for automotive user interfaces differs from the aforementioned design spaces in two main areas. First, all devices are fix-mounted in a car, and it is therefore essential to take placement of the devices into consideration. Second, drivers are limited in their mobility but can act with the left or the right hand, as well as with the left or right foot.

3.2 Examining the Design Space

To be able to provide a comprehensive design space that encompasses all existing controls and their placements in a car, it is necessary to take stock of interior designs of current cars. Since it would be too time consuming to sit in every manufactured car model to perform an elaborate analysis, we chose a smaller but diverse sample of cars to analyze. We visited the IAA 2007 in Frankfurt and took pictures of 117 models from 35 different manufactures. Afterwards, we tagged and categorized a total of 706 photographs and looked for similarities and differences. The photos can be accessed at https://www.pcuie.uni-due.de/AUI/IAA2007.

First, we identified the different input and output modalities that can be found in almost all of the observed cars. Then, we analyzed the position and interaction model for the input and output devices.

3.2.1 Input Modalities

Input devices in the car can be assigned to the three task classes that are described in the introduction. Tönnis et al. [Tönnis et al. 2006] provide a classification in which they distinguish between primary, secondary and tertiary devices. They already roughly assign the task classes to specific locations of the car (see Figure 16). Primary devices are used to maneuver the car, e.g. the steering wheel and the pedals. They are usually mapped one-to-one with their functionality and provide haptic feedback. Primary devices are arranged close to the driver so that they are easy to reach. Secondary devices are, e.g., stalk controls for the turn signal, windshield wipers or other mandatory devices that promote safe driving. They are also at an easy-to-reach distance, often mounted on the backside of the steering wheel. Tertiary devices are used for the infotainment and entertainment systems. They are often placed in the center stack. More and more vehicles come with multifunctional steering wheels, on which a lot of tertiary devices are mounted e.g. radio controls for faster access to frequently-used functions. Thus, an intrusion of tertiary devices into the domain of secondary decices can be observed.

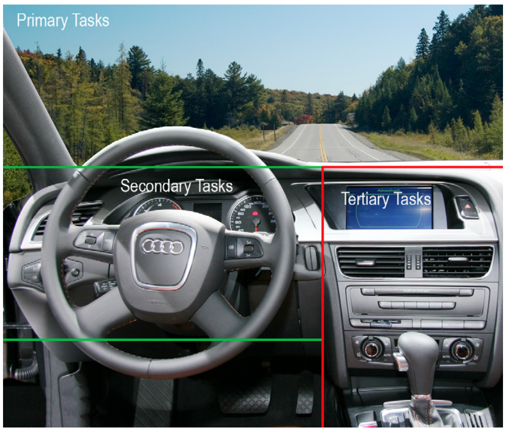


Figure 16. Car cockpit illustrating the distribution of primary, secondary and tertiary tasks (based on [Tönnis et al. 2006]).

Beside assigning devices to the abstract task classes when generating a design space, it is important to look at the physical characteristics of input devices. Despite the high variation of different arrangements of car cockpits, the number of installed input devices in all cars is limited to a few standard controls. By analyzing the set of photographs, we found eight different input possibilities, which are illustrated in Table 2.

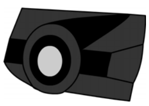
button		slider	knob		pedals
 soft	 mechanical		 continous	 discrete	
stalk control	**thumbwheel**	**multifunc-tional controller**	**micro-phone**	**camera**	**touchscreen**
					

Table 2. Input modalities.

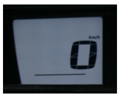
The most commonly used group are buttons, which are present in different sizes and shapes. Nearly all buttons in modern cars are soft buttons. That means there is no permanent haptic feedback available; instead, a visual feedback is often used. For example, when the high beams are turned on, this is indicated to the driver by illuminating a button. In the past, mechanical buttons were used, e.g. to turn on the lights. These buttons provided haptic feedback, e.g. when a button was pressed, it felt pushed in. Thus, the driver could determine the state of the button without looking at it. Sliders form the next group. They are often used for adjusting the direction of the fan. We distinguish between two different kinds of knobs: continuous knobs, e.g. to control radio volume or even the steering wheel, and discrete knobs, e.g. to adjust the air temperature. Stalk controls are often attached to the steering wheel to activate windshield wipers or a turn signal. On a multifunctional steering wheel, thumbwheels are often used to control radio volume. Traditional pedals are still available in the car: gas, brake and (in manual-transmission cars) clutch. Multifunctional controllers can be turned, pressed and sometimes shifted in four or even eight directions. These controllers are combined with high-resolution displays to form the control unit of infotainment and entertainment systems in the car.

New interaction techniques like speech and gesture recognition, as well as indirect interaction like fatigue detection using an eye tracker or cameras, have also found their way into the car. These new interaction techniques provide a means for hands-free interaction so that drivers no longer need to search for and touch specific devices while driving. However, speech recognition often requires the driver to push a push-to-talk button before speaking.

Touchscreens, the last input opportunity, are at the border of the output modalities, because they combine both input and output modalities into a single device. The application areas for touchscreens are infotainment and entertainment systems, as well as comfort systems like air conditioning systems.

3.2.2 Output Modalities

Output devices in cars are used to provide feedback to the user about the current state of the system, e.g. about the current speed, if the turn signal is turned on, or which radio channel is currently playing. Feedback is important but prioritized differently for primary, secondary and tertiary driving tasks. Feedback about the primary task must be immediate and clear, whereas the information about a tertiary task, e.g. which radio channel is playing, is less important.

Visual					
indicator lamp		**display**			
		 	 		
simple	shaped	analog	digital	multi-functional	head-up display

Auditiv	Haptic	
loudspeaker	**vibrating steering wheel**	**mecahnical knob**
		

Table 3. Output modalities.

The output modalities are limited by the human senses, specifically sight, hearing, touch and smell. The primary driving task itself is very demanding on the sense of sight. Any additional visual information forces the driver to draw his attention away from the road scene and that may lead to critical situations. Due to the growing possibilities offered by TFT and LCT displays, visual overloading isn't a trivial issue. On the other hand, this channel provides a means for presenting the driver with permanent, easily recognizable and comprehendible information about the current system status, e.g. illuminating the fuel indicator lamp provides unambiguous information about the gas tank being almost empty. Auditory information eases the demand on the visual channel by providing information in audio form, e.g. alarm sounds or spoken instructions. This information is rather non-permanent and usually requires the driver's immediate attention, e.g. to follow the next navigation instruction or to check which system status indicator just came on. Haptic or tactile information serve predominantly to catch the driver's attention so that more information can be communicated visually. This is because the audio channel is not suitable for conveying complex information. Output modalities that use the sense of smell have yet to be established. However, one can imagine that this sense could be used for more ambient information. For example, if the motor temperature exceeds the normal range, the odor inside the car could change. Further discussion about issues concerning these kinds of output modalities can be found in [Tönnis et al. 2006].

Table 3 shows the different output modalities that can be found in nearly all the cars that we studied. There are a lot of visual indications available in the car to give feedback about current functional states. These indications vary from simple indicator lamps to high-resolution displays. Looking closer at the simple indicator lamps, e.g. those used to indicate that the high beams are turned on, you can find two different ways to present information. One way is to turn on a light above a description (such as the simple indicator lamp in Table 3), and the other way is to illuminate a symbol whose shape indicates the meaning (such as the shaped indicator lamp in Table 3). Visual representations are also used to present information that is directly correlated to the driving task, e.g. actual speed. Both analog and digital representations are used for these purposes. Analog representations can also be divided into displays that use a physical dial and pointer and displays that replicate the dial and pointer virtually. Virtual representations allow for more dynamic use of the space in the middle of the dial to show other information. Digital displays have been used since the end of the 1970s to show alphanumerical information, e.g. the current radio channel or traffic information. With the appearance of LCT or TFT displays in cars, car manufactures started to integrate comfort, infotainment and entertainment functions into single systems, so called multifunctional displays. These systems are controlled by buttons on each side of the screen, a central controller or touchscreen. A further development of display technology in the car is the introduction of head-up displays (HUDs) that show driving-related information directly in the driver's field of view. The visual output appears slightly in front of the car even though it is technically a projection on the windshield.

The sense of hearing is addressed by loudspeakers, which are integrated into the car or embedded in an external device, e.g. a portable navigation system. This modality has long been used for entertainment purposes and has more recently been used for giving aural feedback, especially with voice-operated systems. Due to the arrangement of loudspeakers in some cars, it is possible to provide spatial information over this channel as well. For example, while driving in reverse, an obstacle on the left side could be indicated by sounding a beep from the rear left side.

Information can also be delivered to the driver through his sense of feel or touch. Recently, some car manufactures have added vibration feedback to the steering wheel or to the driver's seat to warn the driver, e.g. of lane departures when no turn signal has been made [@Citroen]. In the earlier days, cars already relied on the driver's sense of touch with mechanical buttons whose physical state gave direct feedback.

3.2.3 Positioning Input and Output Devices

Contrary to the arrangement of input devices in the desktop domain, all devices in the car have to be mounted in fixed positions. Controls have to be always at the same position so that the driver can easily find them without having to take his eyes off of the road. To further help the driver focus on the road, blind interaction through haptic feedback is a research area worth pursuing. Another key aspect for positioning input and output devices is the limitations due to ergonomic factors. All input devices have to be within the driver's reach, so that he can safely manipulate them with either hand or foot while driving. With the exception of touchscreens, visual output devices do not have to be within a safe reaching distance; they just need to be in the driver's field-of-view. Tactile output requires direct contact with the human body, whereas the positioning of auditory output is only important if spatial information needs to be conveyed.

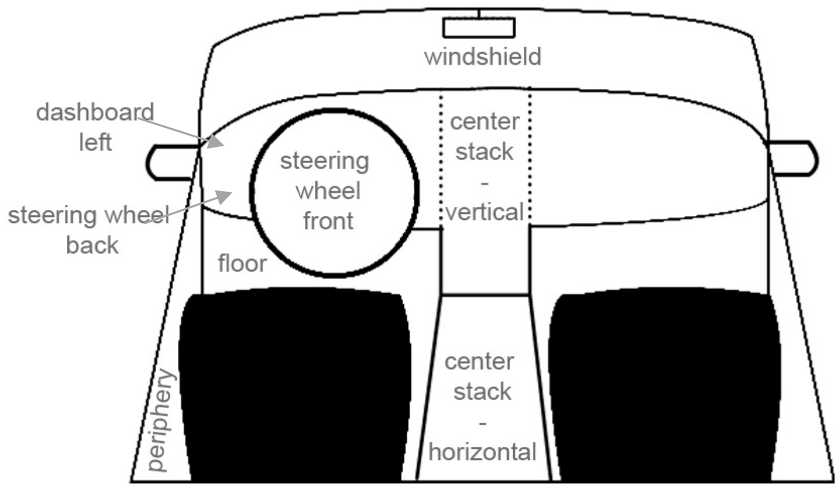


Figure 17. Division of driver's interaction environment.

We identified the following main areas of interaction between the driver and the car (see Figure 17):

- **Windshield**: This can be used as an output device, e.g. with head-up displays.
- **Dashboard**: We focus on the left part of the dashboard that is directly in front of the driver in left-hand drive vehicles.
- **Center Stack**: This is divided into the vertical part (to the right of the "left dashboard" in front of the driver) and the horizontal part (between the front seats).
- **Steering wheel**: This is divided into front and back side of the steering wheel.
- **Floor**
- **Periphery**: This includes the side- and rear-view mirrors.

The area "steering wheel" is a unique case, since it is an input device by itself. However, as mentioned in the introduction, it can still be seen as an integral part of the car, and in order to represent the trend of more and more devices for secondary and tertiary tasks being mounted on the steering wheel, it seems appropriate to consider it as an individual area.

3.3 Graphical Representation

Taking all these aforementioned considerations into account we propose two different graphical representations: one for categorizing a single car and the other for analyzing a set of cars. The latter can be used for comparing cars from different manufacturers or car models from different years.

3.3.1 Categorizing a Single Car

In our two-dimensional graphical representation, we focus on the placement and the task classification of input and output devices based on what body part would interact with them. We regard the driver as the main user and create the interaction descriptions from the driver's point of view.

The first dimension of the graphical representation indicates the placement of devices: windshield, dashboard (left), center stack, steering wheel, floor, and periphery. The other dimension represents the input and output modalities, where input is divided into left or right (hand or foot) as the main interaction initiators. We added one more column for input devices to represent additional modalities, like speech, to the design space. Since voice has no direct spatial representation, it is associated with the periphery area. The output modalities are divided into three areas: sight, hearing, and haptic (for feel and touch). If new interaction methods cannot be located in the current dimensions, a new column can be introduced, e.g. gesture as input or air-flow/olfactory as output, to represent a new modality. Each input or output device can be added as a symbol (see Table 4) into the grid shown in Figure 18.

	primary	**secondary**	**tertiary**
button	#	#	#
slider	#	#	#
knob (d=discrete, c=continuous)	#	#	#
lever	#	#	#
thumbwheel	#	#	#
pedal	#	#	#
multifunctional-knob	#	#	#
warning and indictor lamps	#	#	#
display {f ∈ [a=analog, d=digital, m=multi-functional, h=HUD}	f #	f #	f #
loudspeakers	#	#	#
speech recognition	#	#	#

direct connection between input and output device
indirect connection between input device and output domain

Table 4. Symbolic representations used in the graphical design space.

The symbolic representation of different device types (see Table 4) allows the design space to be extended with new modalities. For example, a sensor to measure skin conductivity that is mounted on the steering wheel would be represented by a new symbol and placed in the section representing the steering wheel. The structure of the design space would remain the same, allowing the new modality to be compared with the others. Thus, the design space is never limited to the current set of modalities.

The three task categories are color-coded in the graphical representation. Numbers inside the symbols indicate the number of occurrences. Dotted lines illustrate connections between input and output devices. Lines ending with arrows represent direct connections. For example, the stalk control for the car's headlights gives visual feedback with an indicator lamp. Lines ending with dots represent indirect connections to an output domain. For example, a volume knob controls audio volume and gives no localized feedback. Numbers on the lines indicate how many controls are connected to the output devices/domain.

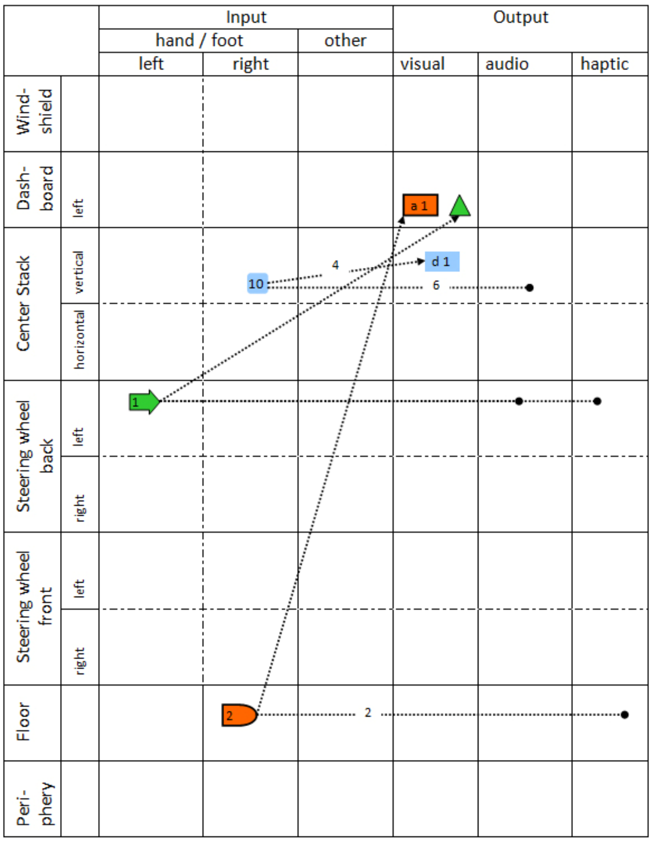


Figure 18. Graphical representation of our design space for driver-based automotive user interfaces with example devices and connections.

Figure 18 shows a graphical representation of a sample automotive user interface. The user interface includes two pedals for the primary task "driving" that provide haptic feedback and visual feedback via a direct connection to an analog display showing the current speed. It also has a turn signal lever (secondary task) that provides visual, haptic and audio feedback by illuminating an indicator lamp, remaining in a specific position and beeping in a rhythmical pattern, respectively. The user interface is rounded out with 10 buttons for tertiary task activities, e.g. adjusting the radio or air conditioning system. Of these 10 buttons, six provide audio feedback and four control a digital display.

3.3.2 Analyzing a Set of Cars

For providing a more general view, an abstract representation of the design space is illustrated in Table 5. The areas are not separated into subareas but instead represented by a triple, which stands for (primary, secondary, tertiary). This abstraction can be used to categorize a set of cars.

	Input		**Output**
	left	right	
Windshield			
Dashboard			
Center stack			(0,0,9-20)
Steering wheel (back)	(0-2,3,0)		
Steering wheel (front)			
Floor			
Periphery			

Table 5. Abstract representation of the design space. Two example entries illustrate the number of input devices for the left side of the steering wheel (back) area as well as the number of output devices for the center stack area.

The example in Table 5 shows abstract representations of input modalities of the steering wheel (back) area and output modalities of the center stack area from a number of cars. The steering wheel representation indicates that a driver can operate zero to two primary devices with his left hand. The variation in the number of devices correlates to the varying number of functionalities provided by each car. For example, in some cars, additional devices for Adaptive Cruise Control (ACC) are needed. Each car also had three secondary devices (e.g. turn-indicator lever) and no devices for tertiary tasks in the steering wheel (back) area. The center stack representation indicates that only feedback for the tertiary task domain is displayed in this area. The number of outputs for this domain range from 9 to 20 and depends on which entertainment, infotainment and comfort systems, e.g. air conditioning, each car has.

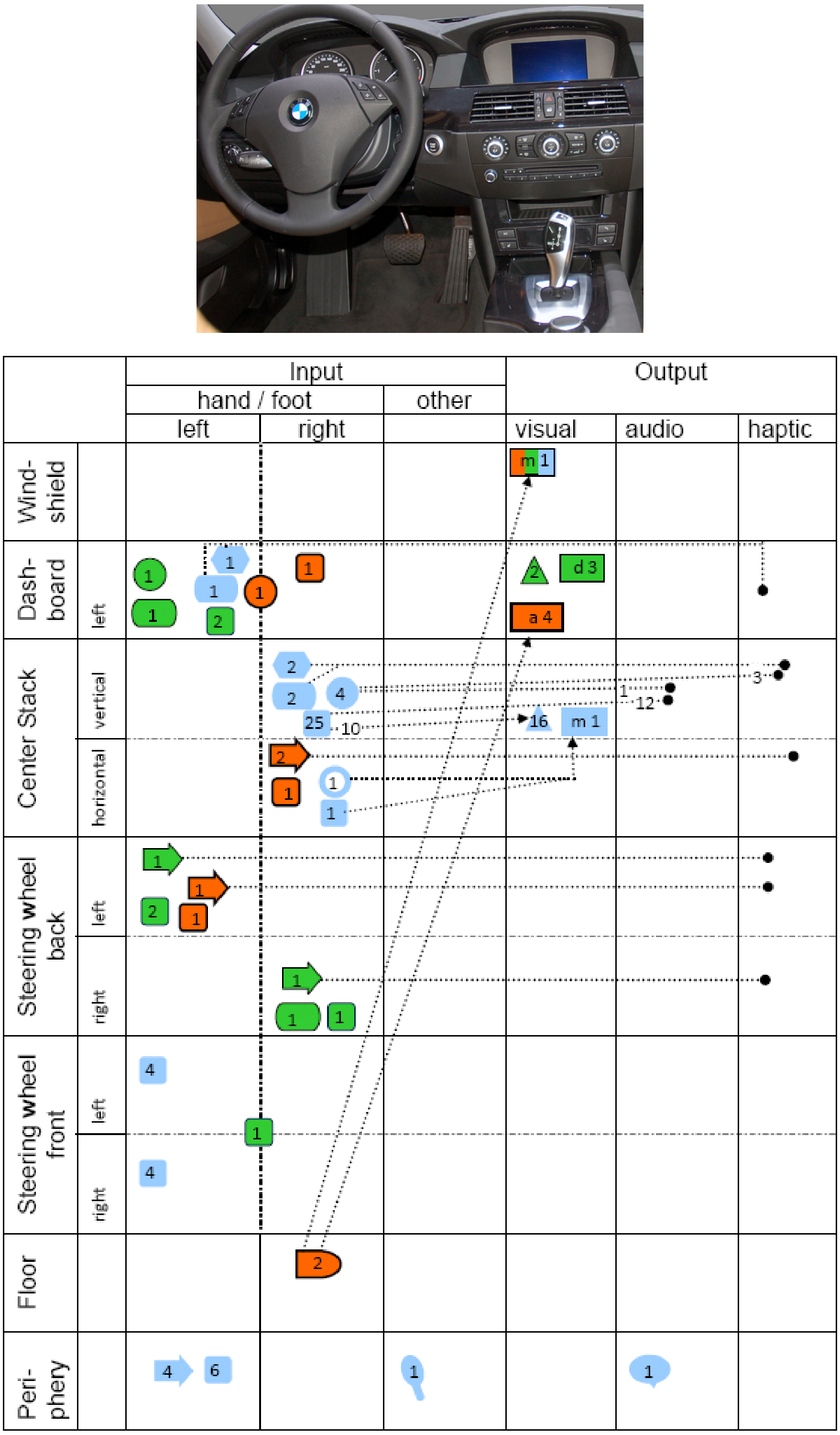


Figure 19. Graphical representation of our design space for a 2007 BMW 5 series. The steering wheel is on the left side.

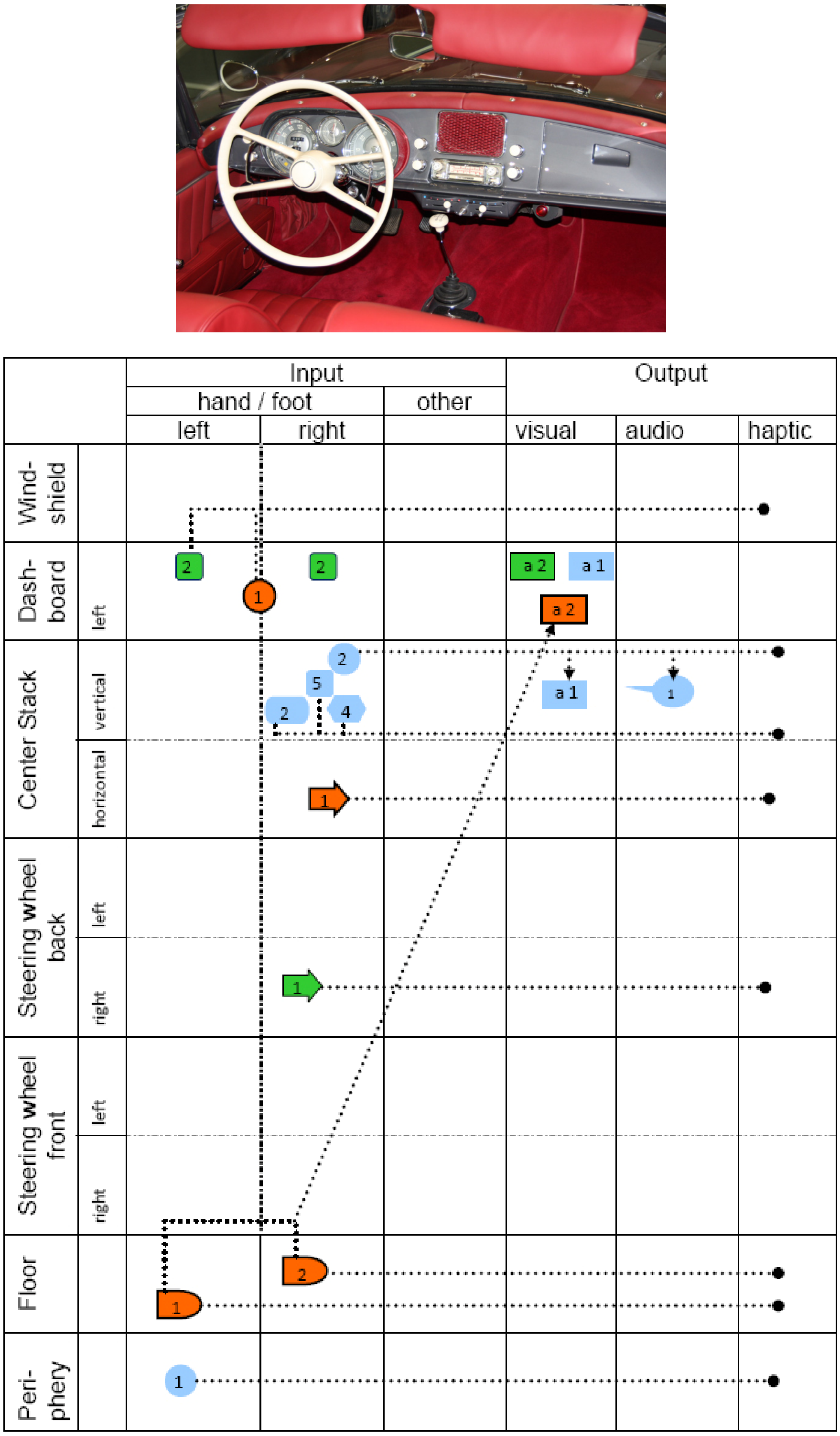


Figure 20. Graphical representation of our design space for a 1956 BMW 5 series. The steering wheel is on the left side.

3.4 Examples of the Design Space

In Figure 19 and Figure 20, two graphical representations for a 2007 BMW 520d and a 1956 BMW 507 are shown. Each input and output device is classified in the graphical representations. Classifying the head-up display was a unique case, since it fits into all three task categories, e.g. it shows the current speed (primary output), if the turn-indicator is turned on (secondary output) and navigation hints (tertiary output). Thus, its display-symbol is divided into three parts, one for each task.

When comparing Figure 19 with Figure 20, the difference in the number of devices is obvious. The 2007 BMW series 5 has 113 devices (13 primary, 15 secondary, 85 tertiary), resulting in the input triple 80 (9, 11, 60) and output triple 33 (4, 4, 25). In contrast, the 1954 BMW series 5 has 29 devices (7 primary, 9 secondary, 13 tertiary), with input triple 21 (5, 5, 11) and output triple 8 (2, 4, 2). Another big difference can be seen in the feedback opportunities of the buttons. All buttons in the 1954 car have haptic feedback while buttons in the 2007 car have predominantly visual feedback. Furthermore, the steering wheel area has become more important. Whereas the 1954 BMW only has secondary controls mounted on the back of the steering wheel, the 2007 BMW has controls for all three task classes on the front and back of the steering wheel. The horizontal center stack area has also gained importance. In the 1954 BMW, this area was only used for the hand brake, and in the 2007 BMW, the main control for tertiary tasks, i.e. the iDrive controller, can also be found here. New display technologies have greatly expanded visual output opportunities in the car and addressed the need to control a growing amount of functionality that has found its way into the car in the last decades. The 1954 BMW provides information exclusively with analog displays, e.g. showing the current speed or the current radio station, whereas in the 2007 BMW, digital displays are predominant. The multifunctional display can inform the user about each function that is available in the car.

Figure 21 illustrates the connection between the symbols used in the graphical representation to real devices for the BMW 520d. In the photograph, the devices are marked by the same symbols. In this BMW series 5, 25 buttons are available in the vertical center stack area, from which 10 provide visual feedback with an indicator light, and 12 provide audio feedback for the radio. The remaining three buttons influence the air conditioning system but provide no direct feedback. The two sliders and thumbwheels provide haptic feedback through their current positions. One continuous knob is used to control the volume, and the other three discrete knobs control the air conditioning system and provide visual feedback by indicating at which temperature they are set. The LCD screen shows visual feedback and is controlled by the iDrive controller, which is mounted in the horizontal center stack. Each of these input devices can be specified further using Card et al.'s design space for input devices [Card et al. 1991]. This center stack example further illustrates that it is possible to analyze a select part of the design space. Still, it must be taken into account that some input-output connections may get lost.

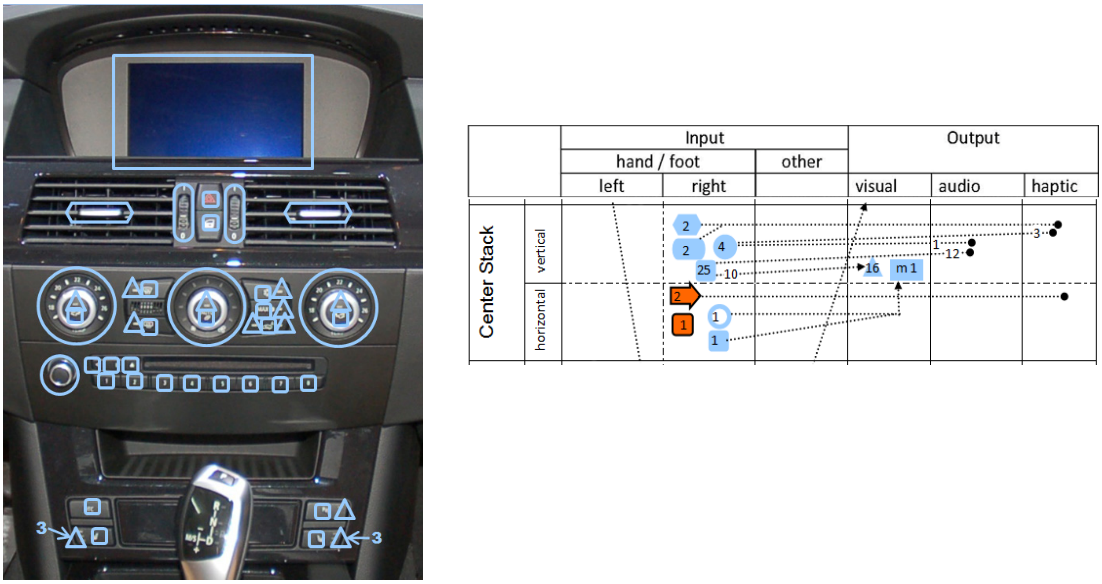


Figure 21. Detailed view of the center stack area. Corresponding markers for the vertical center stack area are shown in the photograph.

Examples for the use of the abstracted graphical design space are shown in Table 6 and Table 7. Table 6 represents a categorization of four different BMWs: series 1, 3, 5, and M3. In Table 7, the number and positions of input and output devices of 8 Renault cars are arranged: Clio, Espace, Kangoo, Koleos, Laguna, Megane, Modus, Twingo.

Analyzing the abstract views of the design space classifications, we found that the BMW models were all very similar in their arrangement of input and output devices, while Renault offered a wider selection of arrangements, especially with devices for tertiary tasks (e.g. the number of controls on the center stack that can be controlled by the driver's right hand range from 6 to 41). These differences are clearly observable, e.g. Renault Espace's cockpit looks very clear and simple with only 6 devices in the center stack area, whereas Renault Koleos's cockpit looks much more complex with 41 devices in the same area.

From these abstract views, similarities and differences can also be extracted. For example, the floor and horizontal center stack areas are very similar. The number of devices in the floor area only differs between automatic and manual-transmission cars from both manufacturers.

<table>
<tr><th></th><th colspan="4">Input</th><th>Output</th></tr>
<tr><th></th><th colspan="2">left</th><th colspan="2">right</th><th></th></tr>
<tr><td>Windshield</td><td colspan="2"></td><td colspan="2"></td><td>(0,1,1)</td></tr>
<tr><td>Dashboard</td><td>(0,4,2)</td><td colspan="2">(1,0,0)</td><td>(1,0,0)</td><td>(4,2-5,0)</td></tr>
<tr><td>Center stack</td><td colspan="2"></td><td colspan="2">(3,0,35-50)</td><td>(0,0,17-20)</td></tr>
<tr><td>Steering wheel (back)</td><td colspan="2">(0-2,3-5,0)</td><td colspan="2">(0,3,0)</td><td></td></tr>
<tr><td>Steering wheel (front)</td><td>(0,0,4)</td><td colspan="2">(0,1,0)</td><td>(0,0,4)</td><td></td></tr>
<tr><td>Floor</td><td colspan="2">(0-1,0,0)</td><td colspan="2">(2,0,0)</td><td></td></tr>
<tr><td>Periphery</td><td colspan="4">(0,0,11)</td><td>(0,0,3-4)</td></tr>
</table>

Table 6. Classification of BMW models series 1,3,5, and M3.

<table>
<tr><th></th><th colspan="4">Input</th><th>Output</th></tr>
<tr><th></th><th colspan="2">left</th><th colspan="2">right</th><th></th></tr>
<tr><td>Windshield</td><td colspan="2"></td><td colspan="2"></td><td>(0,0,2)</td></tr>
<tr><td>Dashboard</td><td>(0,2-4,2-11)</td><td colspan="2">(1,0,0)</td><td>(0-2,0-2,0)</td><td>(0-4,0-3,0)</td></tr>
<tr><td>Center Stack</td><td colspan="2"></td><td colspan="2">(2,0,6-41)</td><td>(0-4,0-3,1-18)</td></tr>
<tr><td>Steering wheel (back)</td><td colspan="2">(0,3,0-4)</td><td colspan="2">(0,5,4)</td><td></td></tr>
<tr><td>Steering wheel (front)</td><td>(0-2,0,0)</td><td colspan="2">(0,1,0)</td><td>(0, 0,0-2)</td><td></td></tr>
<tr><td>Floor</td><td colspan="2">(0-1,0-1,0)</td><td colspan="2">(2,0,0)</td><td></td></tr>
<tr><td>Periphery</td><td colspan="4">(0,0,8)</td><td>(0,0,3-5)</td></tr>
</table>

Table 7. Classification of Renault models Clio, Espace, Kangoo, Koleos, Laguna, Megane, Modus, Twingo.

3.5 Using the Design Space

In the following section we will illustrate for which purposes the presented design space can be used and what we found out when using the design space to analyze the picture taken at the IAA 2007 of 117 different car models. Additionally, we assessed the suitability of the design space by picking a random set of pictures from A2Mac1image database [@A2mac1] and by modeling selected historic cars.

3.5.1 Historical Analysis and Trends

Our proposed design space can be used to analyze trends and explore historical changes. Regarding historical changes, we found that a few controls stayed in the same position, especially those used to control primary tasks. Primary-task controls have not changed at all in the last years (e.g. steering wheel or pedals). The trend towards automatic-transmission cars has only decreased the pedals from three to two. Another trend is in providing greater assistance to the driver while driving and has led to an increase in the number of devices for primary tasks, e.g. for (Adaptive) Cruise Control. In the secondary task domain, analog speedometers have been replaced with digital speedometers, both discrete and continuous ones. Some manufactures have also shifted the visual output of the speed from the driver's side to the middle of the dashboard.

A huge increase in the number of devices for tertiary tasks can also be observed, which is strongly related to the increase in comfort, infotainment and entertainment functionalities in cars, e.g. air conditioning, integrated support for mobile phones, navigation systems, and MP3 players.

3.5.2 Analysis of IAA2007

Using our proposed design space, we were also able to analyze the photographs taken at IAA 2007 in more detail.

One trend that we found is that the space on the steering wheel is often used for controls, e.g. for hands-free interaction with mobile phones or controlling the entertainment system. 78% of the observed cars have controls on the steering wheel. Another trend is the use of displays in cars for navigation systems and other comfort functionalities. 72% of the researched cars already have a built-in display. Display types are evenly balanced between touchscreens and non-touchscreens (46% have a touchscreen). Touchscreens are mostly found in American and Japanese cars, while German cars almost exclusively followed the concept "display controlled with controller".

An indication of future trends could also be seen in the presented concept cars (see Figure 22). Citroen, for instance, has a display and the main controls on the steering wheel in their concept car "Cactus". In general, we observed that the display space in concept cars is much bigger than in current cars. Displays for front-seat passengers are also prevalent.

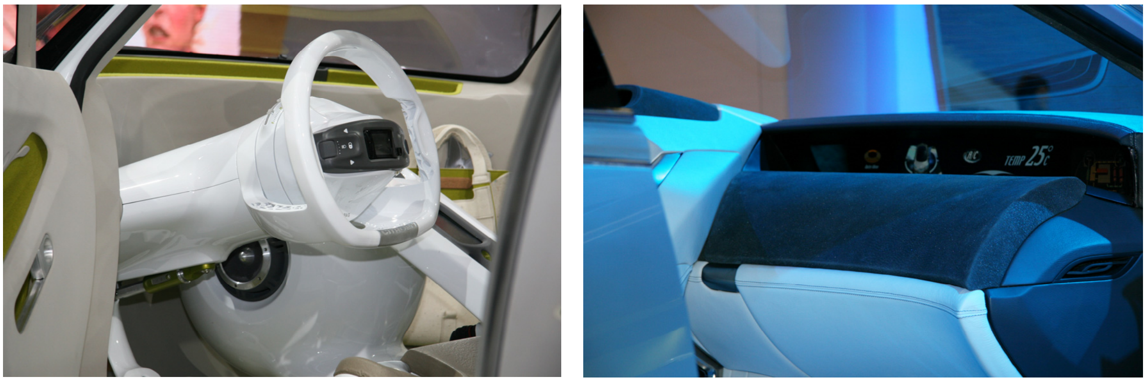


Figure 22. Concept cars showing new position for displays. Citreon concept car Catus (left) has a display mounted on the steering wheel whereas the Hyndai concept car (right) provides visual information through a display integrated on the passenger side of the dashboard.

3.5.3 Looking for New Ideas

With the introduction of automatic-transmission cars, the clutch pedal disappeared, freeing up space for other controls. It would be interesting to see if the left foot could be used for interaction with controls in this space, e.g. for zooming in/out in a navigation system. Currently, input modalities on the steering wheel consist of buttons and thumbwheels. The Citroen concept car Cactus, however, already has a display mounted on the steering wheel. It might be interesting to look more into new input and output opportunities on a steering wheel. Handwriting input on a steering wheel, for example, may be easier than in the center stack for left-handed people in cars with the steering wheel on the left side or for right-handed people in a car with the steering wheel on the right side.

With head-up displays, the windshield is also becoming an important new area for output modalities. In addition to providing visual feedback for systems, the windshield area may also hold opportunities for spatial audio.

The front-seat passenger area also provides open space that is not directly represented in the design space, because it can’t be concretely used by the driver, but one can imagine having an additional screen there where the passenger can interact with in-car systems, e.g. enter entries in the navigation system, and send the results to the driver’s screen.

It is also visible from the design space that new modalities (e.g. haptics) can find spaces that are not yet occupied by other controls.

3.6 Discussion

The central contribution of the chapter is a comprehensive design space for driver-based automotive user interfaces that is grounded in an analysis of a large number of existing cars, including historic cars and concept cars. The design space includes the placement of devices in the car and the human body parts that interact with these devices. To create the design space, we analyzed photographs taken from 117 different cars from 35 manufacturers. We provide an overview of different input and output modalities that are currently available in the car, as well as a division of a car's interior space into 6 main interaction areas: windshield, dashboard, center stack, steering wheel, floor and periphery. The graphical representation can be easily expanded to include new modalities. We chose a 2D grid visualization where one dimension stands for the interaction areas and the other one for input and output opportunities with respect to the body part (hand, foot, eye, etc.) that interacts with the user interface or the human sense that can detect the output (sight, hearing, touch). The different input and output devices are represented by symbols and placed in the grid. With this symbolic language, new trends in complex and combined input-output systems in the car, like augmented reality representations, eye tracking interaction and gesture input, can be easily represented. For example, an augmented reality system can be shown in the grid as a combination of a display in the windshield and a camera in the dashboard area for tracking the driver.

Due to its 2D representation, the design space can be easily extended to include new interaction areas and additional body parts that interact with the system. For example, a new interface that requires the driver to use the right shoulder to press a button mounted on driver's seat would result in a new column for the shoulder, as well as a new row for the driver's seat. By adding new symbols, new input and output mechanisms can also be represented. For example, by adding a new symbol for an eye tracker, systems using eye tracking interaction can be represented. All extensions can be made without affecting the representations of other cars in the design space, and it is therefore still possible to compare cars with different designs and technologies. On the other hand, the design space can be also adapted to possibly changing requirements regarding the positioning areas. For example, if the steering wheel was to be replaced by a joystick as proposed by [Kienle et al. 2009], the rows representing the steering wheel areas would be deleted and a new symbol for the joystick device would probably be introduced in the horizontal center stack area.

In addition to representing a single car, the design space provides a more abstract graphical representation for comparing a set of cars to find concrete similarities and differences between different manufactures or different types of cars, e.g. comparing middle-class and luxury cars. This representation can also be expanded.

The main purpose of the design space of driver-based automotive user interfaces is to provide a common basis for analyzing existing layouts and for generating new ideas. It should be independent of manufacturers and provide a common ground for discussion as well as for documentation. We believe that the graphical design space will enable faster discovery of conflicts between a new concept and the current user interface layout and easier communication of the problems to other team members.

We have used the design space in several projects, where we have explored new ideas for the automotive user interface and developed prototypes. These prototypes will be presented later in this work: e.g. new foot interaction (chapter 6.4.1), handwriting input on the steering wheel (chapter 4.4), and new communication opportunities using a head-up display (chapter 5.5).

4 Supporting Multimodality in Automotive User Interfaces

Different input and output modalities in the car are presented in the previous chapter. In this chapter, we focus on the combination of different modalities and the variation in their placement in the car. First, we will define the term *multimodality*. Next, in the related work section, we focus on tactile as an additional output modality in the car and handwriting as a new means for text input. These two modalities are explored in the two case studies that we present at the end of the chapter. In case study 1 we investigated how vibro-tactile output can be used as an additional channel to provide navigation information to the driver. Our goal was to do so without interfering with the overall user experience and without distracting the driver. This work is published in the proceedings of the conference "Pervasive Computing 2009" [Kern et al. 2009a]. Case study 2 deals with different input and output positions in the car for handwriting interaction and was published as a work in progress at CHI 2009 [Kern et al. 2009b].

4.1 The Term "multimodality"

The initiation of multimodal interfaces goes back to Richard Bolt's "Put-That-There" application that was created in 1980 [Bolt 1980]. He combined spoken commands with a pointing gesture. Since that time, multimodal interaction has grown in importance in the HCI community, largely due to the increasing number of input and output devices for interacting with (ubiquitous) computer systems. In HCI literature, there are slightly different definitions of the term multimodality. It is not within the scope of this chapter to give a comprehensive definition but instead to clarify the term by presenting the basic concepts of multimodality. According to Raisamo [Raisamo 1999], there are two views on multimodal interaction. The first one is rooted in psychology and focuses on the human. In that case, the term modality is related to the human senses: sight, hearing, touch, smell, taste, and balance, as classified by [Silbernagl et al. 1988]. A combination of two or more senses, e.g. providing input by speech and touch, would be a multimodal interaction from a user's perspective. The other view is technology-driven. One definition for this system-centered perspective view is given by Nigay and Coutaz: "Modality refers to the type of communication channels used to convey or acquire information. […] Mode refers to a state that determines the way information is interpreted to extract or convey meaning" [Nigay, Coutaz 1993]. This approach takes into account "the fusion of different types of data from/to different input/output devices" and "the temporal constraints imposed on information processing from/to input/output devices” [Nigay, Coutaz 1993]. Central for the system-oriented view is that the meaning of input data is interpreted. For example, a user interface that provides means for writing a message and recording a voice message for transferring it to another person is not multimodal in the system-centered view, as long as the voice message is only transferred and not interpreted [Nigay, Coutaz 1993]. Literally, a multimodal system supports human modalities by providing a set of multiple modalities. The system is able to understand multimodal input and to choose appropriate output modalities [Coutaz, Caelen 1991].

The main benefit of multimodal interfaces is that the interaction is more natural and flexible, because the user can decide which modality to use. Additionally, the bandwidth of the human can be effectively increased by combining different output channels [Oviatt 1999].

In our everyday working life, multimodality is the norm, and we appreciate it sometimes without even knowing that it is multimodal, because we only use one possible option. For example, a word processing program offers different ways to copy a word: 1) We can select the word with the mouse and press the copy button in the shortcut menu bar, 2) We can select the word by using the keyboard and copy it by pressing “<ctrl>+c”, or 3) When using a speech recognition software, we can select the word with the mouse or keyboard and copy it by saying “copy”.

For user interfaces in the car, multimodality also plays an important role and often combines tactile and speech input. Vilimek and colleagues [Vilimek et al. 2007] discuss opportunities for combining manual controls with speech recognition. One of their major conclusions is that “a key factor for the success of multimodal design is user acceptance” [Vilimek et al. 2007]. This includes driver’s option to choose the input method that is most suitable for the given situation. For example, a driver might feel uncomfortable speaking to the car while other passengers are present and therefore choose to use manual input in their presence. In a situation that requires both hands at the steering wheel, however, the drive would more likely prefer speech input.

Up to now, the human senses sight, hearing and touch have been addressed on the output side in the car while driving. With the introduction of navigation systems in the car, audio is used as an additional channel for providing information. A combination of visual and haptical output can be, e.g. found with multifunctional controller. Such systems often provide haptic feedback in addition to visual feedback. For example, while interacting with the iDrive controller, the driver can “feel” the menu selection move to the next item in a list or to the end of a list, making "eye-free" interaction possible.

In two case studies, we researched different multimodality aspects: vibration output on the steering wheel for navigation instruction (chapter 4.3), and input and output surfaces for handwriting interaction as an additional modality in the car (chapter 4.4).

4.2 Related Work on Tactile Output and Handwriting in the Car

4.2.1 Haptic Output used for Navigation Instruction in the Car

For Advanced Driver Assistance Systems (ADAS), there are already tactile interfaces based on vibration impulses in commercial cars available, e.g. integrated into the seat (e.g. [@Citroen]) or the steering wheel (e.g. [@Audiworld]). In the past few years, the research effort for integrating tactile displays for navigation systems in the cars has grown rapidly. Some of the research projects presented here were performed either at the same time or after our research on vibro-tactile output on the steering wheel was completed. Thus, they have no bearing on our initial assumptions. However, the results have a relevant impact on this research field, and therefore, a short summary of the in part still ongoing projects should be given.

For a meaningful use of tactile information, a direct connection between the actuators and the human body is required. Up to now, the following locations for actuators have been considered by researchers to communicate navigational instructions: driver's seat, steering wheel, and additional wearable devices, e.g. a waist belt used by Asif et al [Asif, Boll 2010; Asif et al. 2010].

In 2004, van Erp and van Veen [Van Erp, Van Veen 2004] compared the effects of providing navigation instructions through tactile output instead of visual output on the driver's cognitive workload and performance. They developed a tactile display that consists of eight tactors mounted in the driver's seat (four under each thigh) and used an ipsilateral mapping, which means vibration under the left thigh indicates a left turn. Distance to the next waypoint was encoded in rhythm (closer temporal intervals indicate that the distance to the next waypoint is decreasing). They observed a reduction of cognitive workload while comparing use of a tactile display to use of a visual display, especially in high-workload conditions. De Vries et al. [de Vries et al. 2009] used a 8x8 matrix of vibrators mounted in the driver's seat for presenting eight different directions.

While the aforementioned approaches where evaluated in a driving simulation setting, Hogema et al. [Hogema et al. 2009] performed a study under real driving conditions and found that drivers were able to localize tactile cues very well.

Asif at el. integrated eight vibration motors into a waist belt and used this device for presenting spatial turn-by-turn information including distance encoding [Asif, Boll 2010; Asif et al. 2010]. On a test track, they compared their approach with a conventional car navigation system and found that using the tactile belt led to better orientation performance than with the navigation system. No differences in cognitive workload, performance and distraction could be observed. They concluded that “a tactile interface can be useful to present more information than simple left or right directions in high load driving conditions” [Asif, Boll 2010].

Vibro-tactile output on the steering wheel is the focus of Beruscha and his colleagues’ research [Beruscha et al. 2010]. In 2010, they published results on a user study that aimed to find out whether drivers steer toward or away from vibro-tactile stimuli that is presented on the left or right side of a steering wheel. In contrast to our approach, they suggest a contralateral mapping for directional vibro-tactile stimuli on the steering wheel.

4.2.2 (Hand-) writing Interaction in the Car

For in-car navigation, infotainment and entertainment systems, text input has become increasingly important. Aside from voice recognition, onscreen keyboards or A-Z spellers operated by a controller are currently the predominant input modalities, and up to now, few alternatives to alphanumeric text input can be found in the research literature.

González et al. [González et al. 2007] investigated the use of EdgeWrite for destination entry in a car context. They mounted a Synaptics StampPad on to the steering wheel where the driver’s thumb is predominantly located. This setup enables the driver to input letters with the thumb following the edge write principle. A character is recognized based on the order in which the four corners of the input space are hit. The authors claim that compared to other selection-based text entry or direct list selection methods, the EdgeWrite gestural text entry method is 20% to 50% faster. This approach seems to be promising but also has a drawback: the drivers have to learn a new specialized interaction. Even if the interaction is very simple, this introduces a steeper learning curve for users.

The learning curve for handwriting recognition, which is a more natural form of text input, would be minimal. Graf et al. [Graf et al. 2008] used single-letter recognition on a touch pad that was integrated into a traditional multifunctional controller mounted on the horizontal center stack. Thus, they used handwriting recognition only as an input modality for their search-based user interface approach. They did not publish any information about user acceptance or potential influence on driver performance but they did report a recognition accuracy rate of 85%.

As far as we know, there are only two studies available in the publically-available literature that look at driver distraction when using handwriting input in the car. Kamp el al. [Kamp et al. 2001] focused on interaction with an in-vehicle Internet browser, such as selecting items, moving a cursor on a map or writing names. Using a lead following scenario in a driving simulator, they assessed the usability of a touchpad, a special keyboard, and voice commands. The 9x7 cm touchpad was mounted on the steering wheel near where the driver's hands are typically placed, and the keyboard consisted of a rotary knob for scrolling through a list of the alphabet. The results led to their recommendation that different input devices should be combined to provide greater benefits for the driver. Some devices performed better for same tasks whereas other devices were outstanding in other tasks. Kamp et al's automotive user interface allowed drivers to browse the Internet while driving. This interface was designed to allow the driver to choose his preferred interaction technique according to the nature of the action and the current driving context. Looking closer at the results regarding handwriting input, it should be pointed out that the touchpad led to significantly less deviation than using the keyboard. Voice recognition was not included in this comparison. Furthermore, task time for using the touchpad was half as long as for using the keyboard and half the number of errors were performed with the touchpad than with the keyboard.

Burnett and colleagues [Burnett et al. 2005] also investigated in two user studies, using a right-hand drive fixed-base driving simulator, the use of touchpads for handwriting text input. In the first study, they compared touchpad interaction with an onscreen keyboard that was operated with a rounded finger joystick. Both input devices were mounted on the vertical center stack on the left side of the driver. Thus, participants (all right-handed) had to use their left hand for interacting with the system. The results show significant differences in dynamic task times and significant differences for speed variability. Handwriting text input was faster while less speed variability could be observed. These results are quite remarkable considering that the driver used their nondominant hand for handwriting input. Subjective ratings about both options show a significant preference to using the touchpad instead of using the onscreen keyboard. In a second study, they addressed the placement of the devices and consequently which hand the driver interacts with. In one trial, they used the same setup as in the first study, and in another trial, the touchpad was mounted on the right side of the steering wheel. Significant differences in glance frequency (the participants looked less often at the touchpad mounted on the right side) as well as speed variability were found (less speed variability when using the touchpad on the right side). Answers given in a questionnaire confirm that it is harder to write with the left hand and therefore more demanding and distracting while driving. Their findings show that handwriting recognition is generally superior to an onscreen keyboard. However, the location of the input device with regard to the dominant hand plays an important role.

Even though research interest in the field of handwriting input in the car seems to be very little, Audi recently added a touchpad for handwriting input to their luxury car A8. It is located in the center stack area and they call it MMI-touch [@Audi (2)]. It is intended to provide more comfort while interacting with the system.

4.3 Case study 1: Tactile Output Embedded into the Steering Wheel

In-car navigation systems are common and many drivers use them regularly. All of these systems provide visual and audio output to convey information about the recommended driving direction to the user. The complexity of the information presented varies from simple directional indicators (e.g. an arrow that indicates the driver should turn right or left at the next crossing) to complex 3D scenes (e.g. a first person view of the geographical surrounding with an added arrow indicating driving direction) and map views. The additional audio information can also vary in complexity, ranging from simple commands (e.g. “turn right”) to longer explanations (e.g. “take the next exit and continue towards highway 7”).

If visual and audio output are present and the driver is only concentrated on the driving task, then current systems work very well. However, in real driving scenarios, drivers engage in many tasks while driving, ranging from conversing with passengers or talking on the phone to consuming entertainment, such as music or audio books. These additional tasks are important to the driver and contribute significantly to the user experience. For example, engaging in a conversation or listening to an audio book can keep the driver alert and may make a trip seem shorter. The audio output of current navigation systems fails to integrate well with these activities and can therefore negatively affect the user experience.

In informal interviews that we conducted, we found the audio output of navigation systems to be an issue for many drivers. They deal with this issue in different ways. A common approach is to mute the navigation system while in conversation or listening to the radio or music and rely exclusively on visual information. However, people reported that this can lead to missing turns as the audio doesn't prompt them to look at the display. In this situation, the driver either has to focus on the navigation system or risk missing important information.

These considerations, and previous work on tactile driver warning systems, e.g. [Ho et al. 2005], motivated us to look at different modalities for presenting navigation information to the driver [Kern et al. 2009a]. Our hypothesis was that vibro-tactile signals might be less intrusive than audio signals and interfere less with other activities. Our study explores the design space of several new modalities for presenting information to the driver. We created a prototype to explore the utility of vibro-tactile feedback in the steering wheel both for the transmission of simple information and as an additional modality that supplements the conventional channels.

4.3.1 Vibrating Steering Wheel – Prototype and Design Space

To build our navigation system prototype, we first assessed potential locations in which to present vibro-tactile output in terms of feasibility and user experience. To make vibro-tactile output useful as an additional modality, a central requirement is that the actuators are in constant contact with the user. This leaves three potential options for integration: steering wheel, pedals and floor, and the driver's seat (see Figure 23).

On the right side of Figure 23, the proposed three placement options in the design space of driver-based automotive user interfaces are illustrated. The driver's seat had to be added as an additional column in the placement dimension, because this position has not been used for interaction devices in the car thus far. The numbers inside the vibration symbol indicate how much vibration motors we would use at the specific locations.

We decided to explore the design space for the steering wheel. The steering wheel is used with hands and fingers, which are very sensitive to tactile information. Additionally, in contrast to the body (driver's seat) or feet (pedals), fingers are usually bare, making it easier to provide rich tactile information.

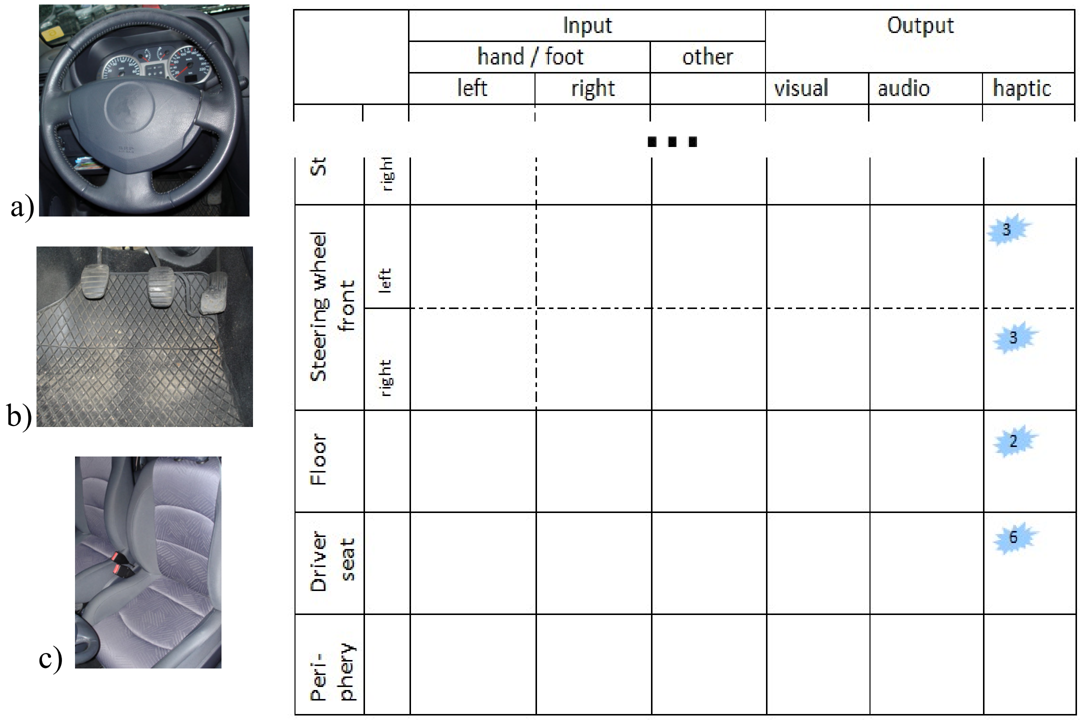


Figure 23. Potential options for integrating vibro-tactile output: a) steering wheel, b) pedals and floor, c) driver seat. On the left side: Graphical presentation in the design space for driver-based automotive user interfaces.

To explore the design space, we created a prototype steering wheel with integrated tactile actuators. An advantage of integrating the signal into the steering wheel is that the signal itself might intuitively prompt the driver to turn the wheel using a direct physical mapping [Norman 1988], nudging and tugging the driver in the correct direction. This approach has been successfully employed, e.g. with a shoulder-tapping system for visually impaired people [Ross, Blasch 2000] which was preferred over and engendered better performance than audio feedback. According to research on stimulus-response compatibility (see [Proctor et al. 2005]), spatially corresponding mappings yield better performance than non-corresponding mappings and matching modes of stimuli and response (e.g. manual responses to visuo-spatial stimuli). This further motivates investigation of vibro-tactile cues in the steering wheel.

The system consisted of a microcontroller (PIC 18F252), 6 power drivers, 6 vibration motors, and a Bluetooth communication module called Linkmatik (see Figure 24). The microcontroller ran a small application that received commands from the serial line (via Bluetooth) and controlled the vibration motors using a pulse-width-modulation via power drivers. Via the Bluetooth module, the prototype can be connected to a test application or the navigation system. Each vibration actuator could be controlled individually with regard to intensity and duration of tactile output. The minimal perceptible duration for the on-time of the motor is about 300ms, and about 5 levels of intensity could be differentiated. Any software capable of sending command strings over the Bluetooth serial link could generate the control commands. In our experimental setup, we used Flash and Java applications on a PC to control the hardware.

The physical design was based on a Logitech gaming steering wheel that is the same size as those found in cars. The vibration motors (6 x 3.5 cm) were integrated on the outer rim of the wheel under a layer of rubber (see Figure 24). It was attached on top of a gaming steering wheel used to control car racing games (logitec). This modified steering wheel acted as the controller for our simulated driving task.

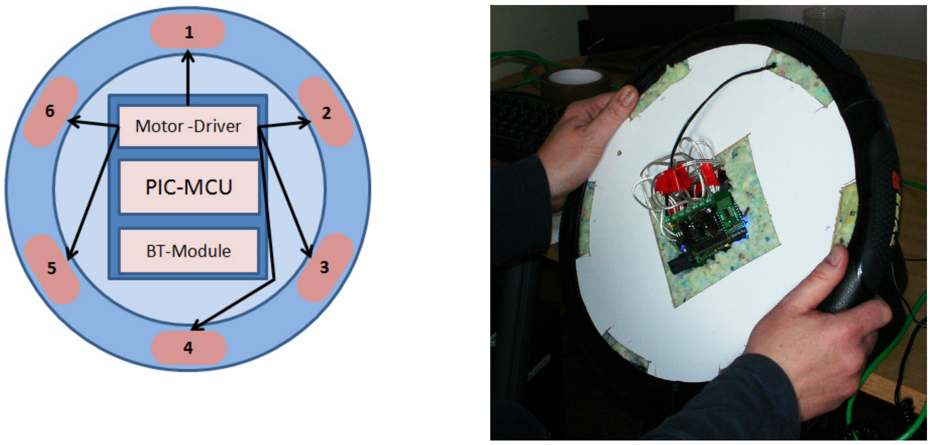


Figure 24. Left: The steering wheel concept and internal data flow. Right: Photo of the prototype used in the study with the elements exposed.

In the design of the tactile output we were able to use the following dimensions:

1) Number of actuators: each of the six actuators could be used independently

2) Intensity: the intensity of each actuator could be controlled independently from an off-state up to level 5

3) Timing of the signal: the actuators could receive signals at any time. This enabled us to create static output (e.g. switching on the left side of the steering wheel with a medium intensity for 2 seconds) as well as dynamic patterns (e.g. activating vibration in a circular pattern moving clockwise, with 1 actuator always on and a brief overlap during transitions).

For our comparative studies, we mainly focused on static patterns because our current setup with only six distinct locations (actuators) for the signal limited the fidelity of dynamic patterns and the speed of the traveling signal. Our static pattern consisted of two different vibration signals:

1) Vibration on the right side (actuators 2 and 3 turned on) indicating that the driver should turn to the right
2) Vibration on the left side (actuator 5 and 6 turned on) indicating a left turn.

However, we also used the study as an opportunity to probe the general feasibility of dynamic patterns. We introduced a dynamic circular pattern, where the vibration signal moves along the wheel. The vibration signal starts at actuator 1 with full intensity. After 300ms, the vibration stops at actuator 1 and starts immediately at actuator 2 for the same duration and with the same intensity. The signal continues traveling around the wheel in this way and indicates the direction in which the driver should turn the wheel, i.e. when it moves from left to right, the driver should turn to the right and vice versa. Dynamic patterns are also an interesting alternative, since they are not affected by extreme turns of the steering wheel and could transmit more complex information. Integrating many small actuators into the wheel would allow the signal to quickly move between adjacent actuators, enabling the user to, for example, feel the vibration move along the fingers of one hand.

In the studies described below, we concentrate on simple static vibration signals. This was feasible because our test situation required no extreme turns. Thus, there was no risk of the wheel being turned around to a degree where a vibration on the left side of the wheel might be felt at the driver's right hand. Participants were instructed to keep both hands on the wheel. To ensure that they felt the vibration regardless of how far their hands were from the closest motor, the vibration signal had to be put on maximum intensity. This unfortunately resulted in some vibration being transmitted to the entire wheel, making it difficult to distinguish between left/right vibration.

4.3.2 Experimental Setup

We ran two studies using an almost identical technical setup to explore the design space. Variations were due to the studies being run in different locations and lessons learned from the first study that affected the design of the second study. Both studies utilized the steering wheel prototype and vibration signal (see Figure 24).

The first study compared three conditions:

- spatially localized audio (beeps provided via headphones)
- tactile-only
- audio+tactile

The second study investigated:

- spoken audio instructions
- visual instructions (arrows)
- multimodal instructions:
  - visual+audio
  - audio+tactile
  - visual+tactile

While the first study aimed to compare signals of similar length and informational content, the second study was designed to closer emulate current navigation systems, which employ spoken instructions.

For the simulated driving task, we chose a deliberately simple road layout inspired by the Lane Change Test layout [Mattes 2003; Mattes, Hallén 2008], see description in 2.6.4. Our road consisted of three straight lanes. The participants had to drive on the middle lane of the road and to change to the left or right lane whenever they received a corresponding instruction and then return to the middle lane again. They also had to obey the speed limit indicated by the road signs they were passing. Order and timing of lane change instructions were randomized.

Figure 25. Setup in the first study with the control panel on a laptop (left), setup in the second study with control panel on a 8" display (middle) and a close-up of the control panel with an direction arrow used in the second study (right).

The chosen road layout offered the opportunity to easily measure direction recognition and driving performance without the risk that the drivers might turn the steering wheel to an angle where the actuators would no longer be at the left or the right side.

Recommended speed limits alternated between 30 and 50 km/h at varying distances. Participants also had to carry out a distractor task.

The physical setup can be seen in Figure 25. Participants were seated on a chair in front of our prototype steering wheel. The logitec driving game pedals were located on the floor and taped to the ground. A 42” display behind the steering wheel emulated the view through the front windshield, showing the road ahead. As a driving simulator, we employed CARS (see chapter 6.5), run on a PC. The CARS software was adapted to send messages to the vibration actuators using UDP over a Bluetooth connection. In the first study, we display the speedometer on a control panel using a laptop located to the side of the driver behind the steering wheel, (see Figure 25). Due to the design of our steering wheel (which was filled in the center with electronics), the control panel could not be placed directly behind the wheel. In the second study, we used an 8” display to show the control panel. This time, we also showed navigation instructions for the visual instructions condition (see Figure 25, middle and right).

The drivers were equipped with a headset that delivered audio information, distracter information and tasks (background music emulating a radio show in the first study and spoken questions in the second study). This headset additionally shielded off audible noise from the vibration actuators.

4.3.3 Study 1: Driving with Audio, Tactile or Combined Directional Information

In the first study, we utilized spatially localized audio (single beeps) as the most direct equivalent to a vibration signal for the audio condition. The audio signal was given by a 140 ms beep following guideline 7 from Green [Green et al. 1993] about the duration of signal bursts. In the vibration condition, two actuators were activated for 300 ms on the left or right side of the wheel (much shorter signals are not noticeable). The third condition combined audio and vibration. 16 participants took part in this study, with the order of conditions counterbalanced.

As a distractor task, participants heard music made to resemble a radio station playing standard easy-listening pop music through their headphones and were instructed to tell the experimenter when they heard a specific jingle. All music tracks were about a minute long, and the jingle lasted three seconds.

To investigate the general viability of a dynamic vibration pattern for conveying directional information, we presented the participants with a final task after they had completed the three conditions. The actuators were turned on one after another to create a signal moving along the steering wheel either clockwise or counterclockwise. Participants did not have a driving task but instead had to hold the wheel and tell the experimenter either verbally or using gestures in which direction the signal was moving. We researched two different conditions: 1) the signal circled once around the steering wheel, meaning that each actuator was turned on only once, and 2) the signal circled twice around the steering wheel.

Design

A within-subjects design was employed, with each subject performing the task in all conditions (in counterbalanced order). Participants were first introduced to the simulator and to the task. The three modalities of directional information were demonstrated: audio, tactile and combined audio+tactile

They were then given six minutes to drive the simulator in order to get used to it with signs on the road giving left-right instructions.

Each condition then lasted six minutes, during which subjects received 18 instructions (nine left and nine right) in random order. The time between instructions was randomly selected from the range 15 to 24 seconds. Subjects were instructed to drive in the middle lane and to switch to the left or right lane according to the signal and then return to the middle lane immediately afterwards. At the end, participants were given a questionnaire and asked to rate the conditions according to their preferences (e.g. being annoying or pleasant). Further open-text explanations (e.g. why it was annoying) of their preferences were collected, as well as demographic data.

As dependent variables, we assessed driving performance, measured in terms of lane keeping (mean deviation from the race line) and compliance to the suggested speed and correctness of lane shifts in both studies.

As a measure of lane keeping, we examined the position of the car on the street in comparison with an ideal race line that we expected participants to drive along (cf. [Mattes 2003]). Every 20 milliseconds, the standard deviation of the mean distance of the car from the ideal race line was calculated up to this point. To make the calculation of the curves to the left and right lane easier, we approximated them also with straight lines, see Figure 26.

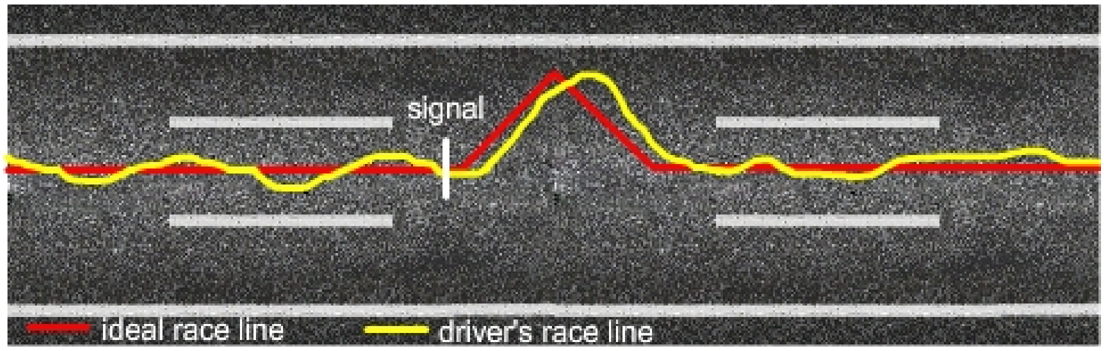


Figure 26. Graphical representation of calculating the driving performance by measuring the standard deviation of the mean distance to the ideal race lane.

Participants

16 participants took part in the study: 9 female and 7 male, aged 25 to 52 (mean of 36). All were administrative or research staff from the Open University. Driving experience varied from having held a driving license from 1 year up to 36 years (mean of 15.3 years). Only 2 people had less than 6 years driving experience. The majority (9 people) drove more than five times per week and only five drove less than once a week. Only one used a navigation system; he reported that he frequently turned off the navigation audio when listening to the radio or talking with other passengers.

4.3.4 Results of User Study 1

Analysis of Driving Performance Data

The effects of representing directional information in different modalities (audio, tactile or audio+tactile) were compared for three measures of driving performance using repeated-measures ANOVAs: likelihood of moving in the correct direction, average speed and mean standard deviation from the race line.

There was an effect of interface condition on participants' accuracy in choosing whether to steer left or right, $F(2, 28)=14.25$, $p<.001$. Planned comparisons showed that participants were correct less often in the vibration condition ($M=16.4$) than in either the audio ($M=17.9$), $p<.01$, or combined condition ($M=17.9$), $p<.005$. There was no significant difference in accuracy between the audio and combined conditions, $p>.05$. There was no significant effect of the modality of directional information on the average driving speed, $F(2, 30)=2.42$, $p>.05$. There was also no effect of the modality of directional information on the standard deviation from the race line, $F(2, 30)=1.04$, $p>.05$.

Therefore, we can conclude that the tactile information led to decreased driving performance compared to the audio, and there was no improvement in providing both together. There were, however, interesting qualitative responses to the different modalities from participants in the questionnaire. These are outlined in the next section.

All participants were able to distinguish the direction of the dynamic vibration signal in the follow-up experiment. The variation of having the signal run twice around the wheel was preferred, as this provided a confirmation of the initial judgement. This indicated that the fidelity of the signal (created with only six actuators) was not high enough to be easily detected.

Analysis of Questionnaire Results

The questionnaire asked participants to rate the output modality variation they preferred and to what extent they found each pleasant, annoying or distracting. There was no significant effect of interface condition on the rating of pleasantness, annoyance or distraction. However, 11 participants were found to prefer the audio-only interface and 5 preferred the combined interface. No participant preferred the vibration interface. A Friedman's ANOVA found differences in participants' preferences for different navigational systems to be statistically significant $\chi^2 = 11.37$, $p<.005$. Post hoc Wilcoxon tests indicated that the audio condition was preferred to the combined condition ($p<.05$), which was in turn preferred to the tactile condition ($p<.05$).

All of the participants in the first study gave extensive answers to the free-text questions in the questionnaire. They were asked to explain what they liked and disliked, and what was annoying, pleasant or distracting in the three conditions, as well as what the advantages or disadvantages were. Their answers, as well as remarks by participants during the study, indicate that the preference for the audio condition was mostly due to difficulties in distinguishing the direction of the signal and the limitations of our prototype. One limitation that hindered participants in detecting the signal direction is that the vibration was transmitted across the entire wheel and could not be easily pinpointed to a specific point in the wheel. This was a side effect of the prototype design to use a maximum intensity signal to ensure that participants could feel the vibration regardless of where they held the steering wheel.

Almost two-thirds of the participants mentioned difficulties in distinguishing direction and location of the tactile vibration signal, possibly due to the insufficiencies of our current hardware implementation. Vibration on its own was considered to be less clear or comprehensible than the audio signal. Several participants thought there was a risk of confusing the signal with road vibrations or it being masked. As a practical issue, several participants mentioned that it might be hard to notice if only one hand is on the wheel (although this issue might be alleviated by a more sophisticated setup with many actuators). One possibility is that integrating more actuators into the steering wheel, increasing signal fidelity and reducing its intensity for a more localized signal, would provide a remedy to most of these issues except for the potential interference of road vibration.

Many general problems were listed for the audio-only condition, confirming our hypothesis that alternative modalities would be useful. Half of the subjects mentioned that background noise, conversation and radio could interfere, mask the signal or distract the driver. As a practical issue, hearing impairments were mentioned. The utility of spatially localized sound instead of verbal instructions was questioned, e.g. the audio signal could be masked by other sounds (although it should be noted that the beep signal was used more for reasons of experimental parity than practical utility). Several participants commented on the audio being annoying. Thus, it seems that verbal instructions are superior to more abstract sound, even if they might feel tedious to listen to.

Overall, problems in one condition mirrored advantages of the other: Several people who mentioned background noise/radio as a problem for audio signals listed as an advantage of vibration that it would not be masked by surrounding noise, while the audio signal was listed by the majority as being “easier to notice” and to “distinguish direction”.

Participants almost unanimously liked the multimodality of the audio+tactile condition. Its main advantage was seen in providing confirmation and reinforcement of the signal perceived in the other modality, and a backup in case one signal was missed, “[the multimodality] alert[ed] more than one sense not to miss [the driving instruction]”, “the sound reinforced the vibration”, and “the sound will confirm the vibration if the driver [is] not sure”. A few people were concerned that an inconsistency in the combined signal would be highly confusing and that the combination of two modalities might become overwhelming or distracting when experienced over an extended period of time.

The questionnaire results led us to continue to explore the design space and to focus on the utility of vibration as auxiliary information. Results and user feedback indicated that this might be a likely avenue for finding benefits. It was also encouraging that performance measures for speed and race-line for the vibration-only signal were comparable across conditions despite our prototype’s limitations. User feedback confirmed our hypothesis that audio information on its own is considered problematic in real-world driving due to interference with the radio and passenger conversations. Vibration-only information might be a better approach, but needs to be evaluated further with much better prototypes (that produce better signal resolution). Further research in this direction will need to keep in mind users' concerns about one-handed driving and the possibility of road vibrations masking the signal.

4.3.5 Study 2: A Comparison of Different Forms of Multimodal Directional Information

The questionnaires in the first study revealed a range of concerns regarding spatialized audio, e.g. use of headphones while driving, and danger of confusing directions when turning head during the audio signal. Furthermore, a spatially localized audio beep is too restricted in terms of the information it can convey to be useful for complex driving instructions. The second study therefore investigated a more realistic scenario that emulated existing navigation systems. This study investigated whether multimodal information improves performance and whether an auxiliary vibro-tactile signal would outperform the existing combination of audio and visual information.

Design

A within-subjects design was again employed. Participants took part in 5 conditions in counterbalanced order: only audio, only visual, audio+visual, visual+tactile, audio+tactile. Information was presented via spoken audio instructions, e.g. "please change to the left/right lane", by a female computer voice, and in the visual conditions, through an arrow next to the speedometer indicating the direction. The vibration signal, again, was given for 300 ms by two actuators on the left or right side of the wheel.

An audio distractor task was designed to emulate distractions from passenger conversations that interfere with audio navigation information. It consisted of arithmetic problems that participants needed to solve, e.g. "Peter and Paul are 16 together, Paul is nine, how old is Peter?". There was a 10-second interval between questions. The volume of questions was lower then the audio instructions. Participants also had to pay attention to visual information by looking out for signs indicating the speed limit and making sure they did not go too fast or slow. All other aspects of the design were identical to the first study.

Participants

17 Master's students from the University of Duisburg-Essen participated in the second study: 2 female and 15 male, aged between 23 and 35 (mean=26). Driving experience varied from having held a license for between one and 12 years (mean of 7.8).

6 typically drove less than once a week, another 6 between one and four times a week and 5 five to seven times. Half of the participants (9 people) used a navigation system. Six reported that they found voice output inappropriate or disturbing when talking with passengers or listening to the radio. One reported turning the system off while talking to people and another when listening to the radio. Three never turned it off. Participants who used a navigation system were asked to specify on a scale from 0 (very often) to 5 (never) how often they miss turns while the voice output is turned off. The mean result was 2.96 (standard deviation 0.94).

4.3.6 Results of User Study 2

Analysis of Driving Performance Data

Participants' driving performance with each of the five representations of directional information (audio, visual, visual+audio, audio+tactile, visual+tactile) were compared using repeated-measures ANOVAs. Modality of the information had no effect on the number of correct lane changes $F(1.9, 30.3)=2.45$, $p>.05$. There was also no effect of the modality on the average speed, $F(1, 16)=1.21$, $p>.05$. However, there was a significant effect of information modality on the standard deviation from the race line, $F(4, 64)=3.40$, $p<.05$. Mean standard deviations from the race line are shown for each condition in Figure 27.

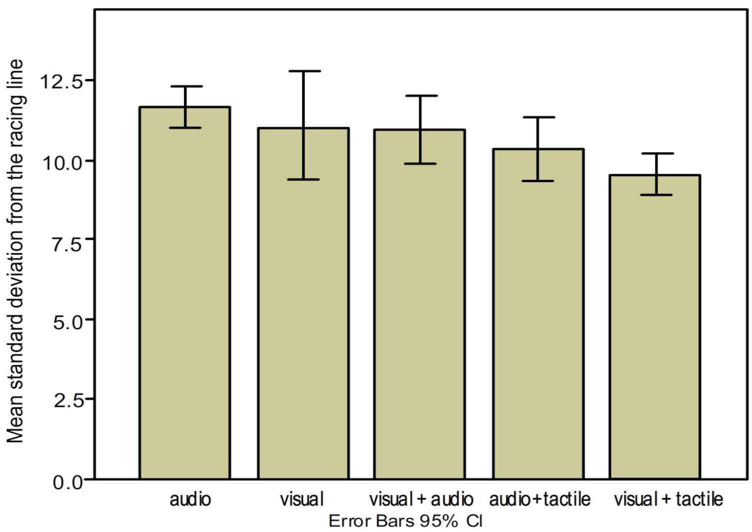


Figure 27. Mean standard deviation from the race line by condition. The combined tactile and visual condition has the lowest mean standard deviation.

Pairwise comparisons revealed that there was a significant improvement in performance when coupling audio with tactile information compared to audio alone ($p<.05$); however, there was no improvement when coupling audio with visual information compared to audio alone ($p>.05$). There was also an improvement in coupling visual and tactile information over visual information alone ($p<.05$), but no improvement over visual alone when coupled with audio ($p>.05$). There was no significant difference in performance between the audio+tactile and visual+tactile conditions ($p>.05$).

Questionnaire Data: Preference ratings

Participants were asked to rate each of the five navigational system configurations in terms of preference from 1 (most preferred) to 5 (least preferred). Preference scores were compared using Friedman's ANOVA. A significant effect of the type of navigational system was found on participants' preferences ($\chi^2(4)=43.77$, $p<.001$). Wilcoxon tests were carried out to follow up on this finding. A Bonferroni correction was applied, so all effects are reported at a $p<.007$ level of significance. Both the visual+tactile (Mdn=1, T=3.71, p=.001) and visual+audio (Mdn=3, T=2.81, p=.005) configurations were preferred to the visual alone (Mdn=5). Similarly, both the audio+tactile (Mdn=3, T=2.76, p=.006) and visual+audio (T=3.10, p=.002) configurations were preferred to the audio alone. The visual+tactile configuration was also preferred to the other two multimodal configurations: visual+audio (T=3.70, p=.001) and audio+tactile (T=3.25, p=.001). There was no significant difference in preference for the audio+tactile and visual+audio configurations. Therefore to summarize, multimodal are preferred to single modal navigational systems, and the most preferred multimodal configuration uses visual and tactile representations.

Questionnaire Data: Ratings of Pleasantness and Annoyance

Participants were asked to score how pleasant and annoying each of the navigation systems were to use, indicating their preference by crossing a line. The distance along the line was then measured and translated into a scale ranging from 0 (not at all) to 5 (very). Mean ratings are shown in Figure 28 for both pleasantness and annoyance.

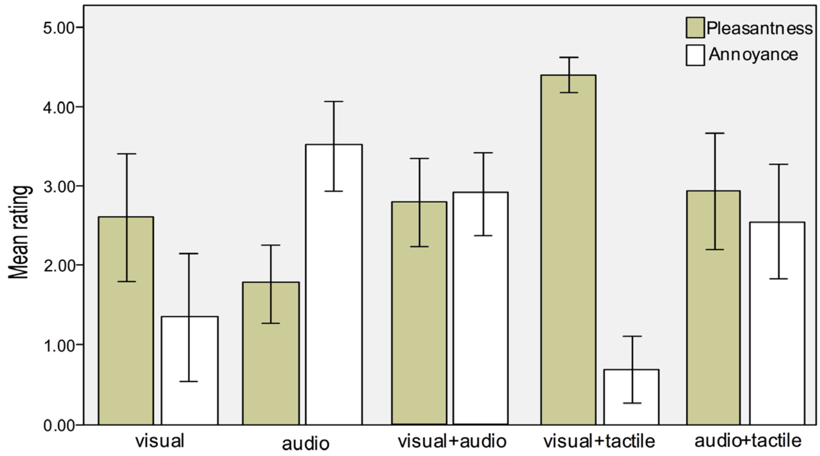


Figure 28. Mean rating of how pleasant and annoying the conditions were perceived to be (0=not at all pleasant / annoying, 5=very pleasant / annoying).

Mauchly's test indicated that the assumption of sphericity had been violated for the pleasantness scores ($\chi^2(9)=27.6$, $p<.05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.49$). A significant effect of navigational system was found on pleasantness ratings, $F(2.0, 31.4)=12.3$, $p<.001$. Planned contrasts revealed that visual+tactile was found to be more pleasant than only visual ($p<.001$), visual+audio ($p<.001$) and audio+tactile ($p<.005$). No significant differences were found between the audio and visual+audio ($p>.05$) or audio+tactile ($p>.05$).

Mauchly's test also indicated that sphericity had been violated for the annoyance ratings ($\chi^2(9)=31.7$, $p<.05$)), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.54$). A significant effect of navigational system was again found, $F(2.2, 34.6)=16.7$, $p<.001$). Planned contrasts revealed that participants found no difference between visual+tactile and only visual in terms of how annoying they were ($p>.05$), but found the visual+audio to be significantly more annoying than either only visual ($p<.005$) or visual+tactile ($p<.001$). Adding vibration ($p<.01$) or visual representations ($p<.05$) to audio were found to make it significantly less annoying. Audio+tactile was found to be significantly more annoying than visual+tactile ($p<.001$).

In summary, participants tended to find the visual+tactile representations both most pleasant and least annoying. The audio navigational system was found to be particularly annoying and unpleasant. This effect was ameliorated somewhat by combining it with another representation, i.e. tactile or visual.

Questionnaire Data: Ratings of Distraction

Participants were also asked to rate how distracting they found each of the navigational systems, again by crossing a line representing a scale between 'very' and 'not at all'. Mean ratings of distraction are represented in Figure 29.

Mauchly's test indicated that the assumption of sphericity had been violated for the distraction ratings ($\chi^2(9)=19.3$, $p<.05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.58$). A significant effect of navigational system was uncovered, $F(2.3, 37.0)=4.8$, $p<.05$. Planned contrasts revealed that participants perceived the only visual system to be more distracting than the visual+tactile ($p<.001$), but no more distracting than the visual+audio system ($p>.05$). The audio system was perceived to be neither more nor less distracting than the audio+tactile system ($p>.05$) and the visual+audio system ($p>.05$). The visual+tactile system was perceived to be less distracting ($p<.05$) than the visual+audio system.

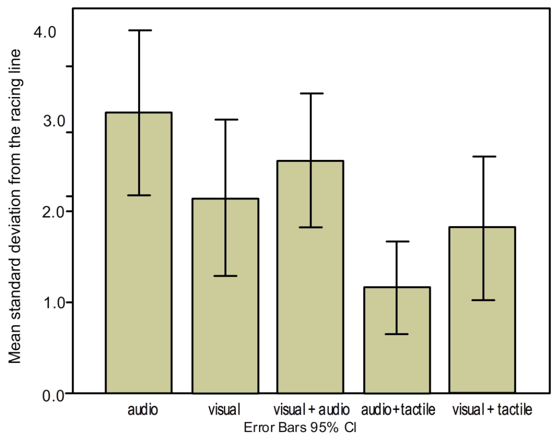


Figure 29. Mean rating of perceived distraction (5=most, 0=least distraction). The visual-only and the visual+audio condition are considered most distracting.

Questionnaire Data: Summary

The navigational system that combined visual and tactile information came out as a clear winner in participants' questionnaire responses. In the preference ratings, it was preferred to all other modality variations. Multimodal systems were also preferred generally to the single modality systems. The visual+tactile system was found to be the most pleasant system to use, as well as the least annoying and the least distracting.

The most frequently listed advantage for the audio condition was that audio information allows the driver to keep their eyes on the road (7 times) and that it is very salient

(4 times). As a disadvantage, interference with conversation was listed, and that it can quickly become annoying. Participants seemed to perceive as an advantage of the visual information display, in that it does not distract from driving or listening to passengers. Four people mentioned that its biggest advantage is that the information can be glanced at a second time instead of having to remember the information. Visual information was considered useful as a confirmation or backup for another signal that may not been well understood or clearly perceived, especially since it does not disappear and can be looked at again. The backup/confirmation function was listed frequently for all of the multimodal conditions.

The biggest disadvantages of visual information, listed most often, are that it requires the driver to look away from the road (listed 10 times) and can be missed, since it can only attract the driver's attention when the driver is looking at the display. An auxiliary channel, either audio or vibration, was seen as a remedy to both disadvantages. Few people listed any disadvantages for the visual+tactile condition, while visual+audio was listed by some people as having the 'disadvantages of both'. Vibration was valued as more ambient and less distracting by a few people and also listed as being fast and providing the least distraction from traffic or conversation.

4.3.7 Limitations and Potential Improvements

The studies were conducted in a simulator setting and not in a car. Hence, there were no vibrations induced from the actual driving. Current cars have a suspension mechanism that ensures few road-triggered vibrations can be felt in the car and, in particular, in the steering wheel. We expect that the results acquired with the simulation environment are similar to those in an actual car.

Due to our prototype hardware setup, we have tested the general viability of using vibration signals using a fairly rough-grained signal (only 6 actuators and switching times of 300ms). Participants were able to identify the information from static (left side or right side vibrates) signals well, leading to improved performance. They were furthermore able to distinguish a dynamic pattern of the vibration moving directionally around the wheel (clockwise or counterclockwise). However, the small number of actuators and the long switching time of our prototype consequently made the pattern too 'slow' to be utilized during a driving task. Even with these limitations of using a static signal (instead of a dynamic pattern), we were able to achieve a better user experience. We expect that with more actuators distributed throughout the steering wheel and a faster-moving signal, the experience could be further improved. These changes would allow the vibration to be felt moving between the fingers of one hand on the wheel and suitable for one-handed driving.

4.3.8 Discussion and Conclusions

In the case study described in this section, we investigated the effects of presenting vibro-tactile information to the driver [Van Erp, Van Veen 2001; Ho et al. 2005]. In particular, we looked at the effect of presenting navigational cues with vibration output embedded into the steering wheel. Our hypothesis was that the cognitive load associated with standard navigation systems on the driver could be minimized by presenting tactile information, since most driver distractions are either visual or auditory. The results of the first study indicated that vibro-tactile information display may not be as beneficial as more conventional auditory display of information in a distracting environment. This was because participants found it more difficult to perceive the direction represented by the tactile information and thus made more mistakes. Largely because of this, the participants preferred an auditory interface. We predict that tactile output in our prototype could be improved upon to increase the perceptibility of information (e.g. by using tactons [Brewster, Brown 2004]). However, based upon our user feedback, we chose to pursue a different approach of investigating whether representing redundant information in the tactile modality might be beneficial and favoured over single modality setups. In the second study, we investigated whether multimodal representation of directional information would be associated with improved driving performance compared to single modality visual and audio representations. We also compared users' qualitative impressions of the different systems using questionnaires.

As predicted, we found the best driving performance in the conditions where there was redundant multimodal representation of information. However, this performance improvement was only found in the two conditions where audio and visual representations were coupled with vibro-tactile representation and not where only audio and visual representations were combined. As the task carried out by the participants was highly demanding on their visual and auditory attention, one plausible explanation for this finding is that the participants were able to use the tactile information as an indication of when to pay attention to the other forms of information being presented. This would enable them to offload the cognitive work associated with monitoring for navigational information in the auditory or visual modalities and allow them to concentrate on the driving and auditory distracter tasks (cf. [Scaife, Rogers 1996]). Some participants indicated in the questionnaire that they relied primarily on the tactile representation for navigational information but were able to use visual or auditory information as a backup whenever they were unsure which direction had been indicated.

This finding is supported and augmented by the questionnaire findings: participants showed a strong preference for the multimodal navigational interfaces, and, in particular, visual information coupled with tactile information. Participants reported finding audio information on it's own distracting when they were engaged in conversation. This led to an unpleasant experience and annoyance, which could be partially ameliorated through the simultaneous provision of tactile information.

4.4 Case study 2: Handwriting Text Input while Driving

Current methods for text input in the automotive context concentrate mainly on three approaches: (1) touch-based direct input with onscreen keyboards, (2) a set of tangible controls (i.e. physical knobs, sliders, buttons) with an onscreen keyboard, and (3) voice recognition. In contrast, our work looks at using handwriting recognition for text input [Kern et al. 2009b]. We address the following central questions that arise when designing a handwriting recognition system for use while driving:

- Where should the input surface be located?
- Where should the visual feedback be presented?
- How does text input impact driving behavior?

4.4.1 Prototype

The results reported by [Kamp et al. 2001; Burnett et al. 2005] show that handwritten input has some advantages compared to using an onscreen keyboard. Hence, we designed a user study to explore potential setups in a car cockpit. Keeping Burnett et al.’s [Burnett et al. 2005] concerns regarding text input on a steering wheel in mind, we nevertheless decided to try their idea of having a text input interface mounted on a steering wheel. In contrast to Kamp et al.’s approach [Kamp et al. 2001], we placed the input surface at the middle of the steering wheel, because it is the most independent position for left-handed and right-handed drivers in both right-hand and left-hand drive vehicles. Since the center stack has already been used for handwriting recognition, e.g. in [Graf et al. 2008], we decided to compare the steering wheel to the center stack as text input interfaces under different feedback conditions (feedback on the active input interface vs. feedback in the dashboard display). Both input locations were easily reachable from the driver’s seat. This led to four different interaction options, illustrated in Figure 30. In option 1, a display on the steering wheel is used as the input and output device. In option 2, the driver used the display on the steering wheel only for inputting text, and the visual feedback was presented on a screen in the dashboard area. In option 3, the display for input and output was located in the horizontal center stack. Finally, in the 4th option, the display in the horizontal center stack area was used for text input, and the feedback was provided on a screen in the dashboard area.

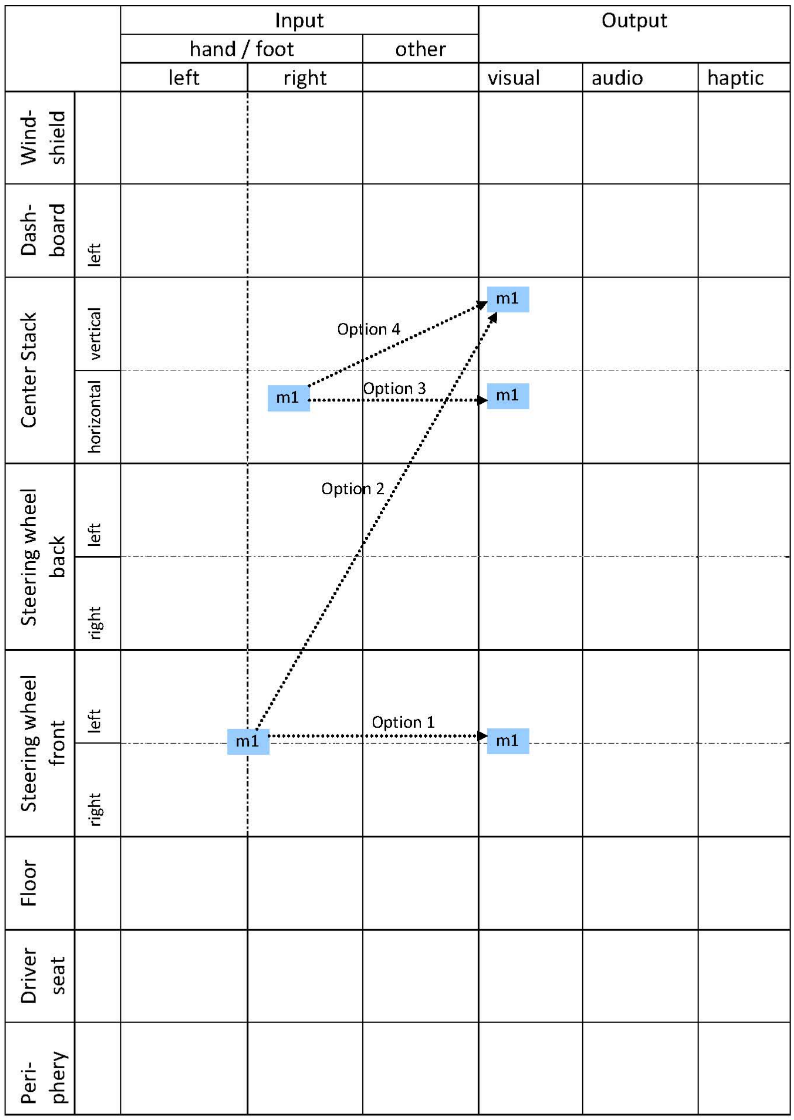


Figure 30. Graphical presentation of the four different input/output combinations for handwriting input while driving.

4.4.2 Experimental Setup

In Figure 31, the overall hardware setup in the experiment is displayed. The setup was created to simulate a driving situation with a left-hand drive vehicle, complete with a steering wheel and pedals. A first person view of the road s presented on a large screen

(42” TFT monitor), and the speedometer and other instruments are shown on a dashboard screen (15” laptop display). Due to the construction of this setup, the driver would not be able to see a dashboard screen behind the steering wheel. Therefore, we decided to put the dashboard screen to the right of the steering wheel, like it is in some new cars, e.g. Citroën C4. In some conditions, this dashboard screen is also used to display visual feedback for handwriting input (see Figure 33). For touch input, we used two 8” TFT color touchscreen displays. One display was integrated into the steering wheel (a Logitech racing steering wheel with a normal-sized steering wheel mounted on top). The other display was integrated into the horizontal center stack to the right of the driver. These displays were also used for visual feedback in some of the conditions.

Figure 31. Study setup: Touchscreen displays on the steering wheel and in the horizontal center stack serve as input and output interfaces. Laptop serves as dashboard display (and speedometer). 42” TFT monitor shows first person view of the driving simulator.

For online handwriting recognition, we used the Ink Analysis and Recognition API from Microsoft [@msdn.microsoft]. We developed test software with two different graphical user interfaces:

- *direct feedback* – the recognized character is directly shown on the same screen (see Figure 32)
- *indirect feedback* – the recognized character is shown on the dashboard screen (see Figure 33).

The written character is immediately shown in both user interfaces. In the experiment, we restricted the handwriting recognition to recognize only single letters (A-Z and a-z) and backspace (“/”). If a text input is not recognized, a short audio feedback (beep) is provided; for recognized characters, no audio feedback is presented, however, when a word is completed, positive audio feedback is given.

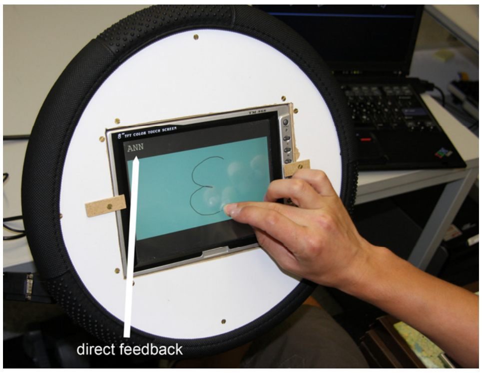


Figure 32. Graphical user interface of the prototype *direct feedback*. Recognized characters shown above the input area.

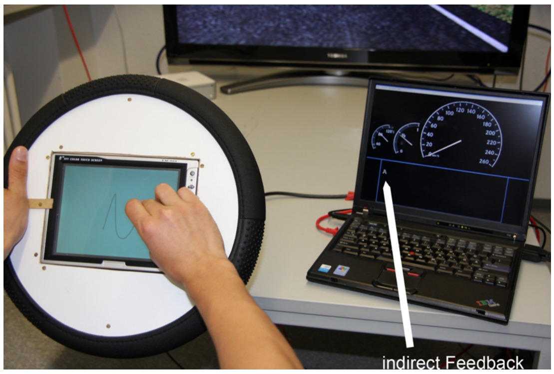


Figure 33. Graphical user interface of the prototype *indirect feedback*. Recognized characters shown on the dashboard screen.

In order to create a realistic driving situation and also measure the driving behavior and driving performance, we used CARS, which is described in more detail in chapter 6.5. The driving environment used in the study was a track with straight roads, three left curves, three right curves and an intersection where the drivers have right of way. Speed limit signs next to the road indicated the assigned speed limit (e.g. 30km/h, 50km/h). The participants had to drive on the right side and there was no other traffic on the road.

4.4.3 *Subjects*

We recruited 16 participants (5 female) for the study. The average age was 24.88 (SD=3.36), and they were all right-handed. All participants have carried a valid driver's licenses for 6.5 years (SD=2.81) on average. Regarding driving behavior, nine participants indicated that they drive less than 10,000 km per year, four drive 10,000-20,000 km per year, and three drive 20,000-30,000 km per year. All participants were used to driving left-hand drive vehicles. Their use of touchscreens, however, varied: six participants never worked with touchscreens, one uses them regularly, and the rest use them occasionally.

4.4.4 Study Design and Procedure

We chose a within-subjects design with two independent variables: the position of the input surface and the position of the visual feedback. We explored the four different conditions (input surface/visual feedback):

- steering wheel/steering wheel
- steering wheel/dashboard

- center stack/center stack
- center stack/dashboard

We measured the following dependant variables:

- driving task performance (lane keeping defined by standard deviation of the mean distance to the racing line and average speed)
- text input speed (character per minute (cpm))
- corrections and remaining errors.

We used four counterbalanced sets of tasks that were randomly assigned to the different conditions. For the tasks, the input words were compromised of 10 strings, alternating between addresses (street names and city names, e.g. *Berlinerstr Bonn*) and first names (e.g. *Anna*). Entering addresses is a common task in navigation systems, and entering names is common for finding contacts in the phonebook. The length of addresses ranged between 15 and 17 characters; names were 4 to 6 characters long. The total number of characters in each task was the same. In each task, the participants had to write (using a finger) the given text strings on the specified touchscreen surface while driving. Participants were asked to maintain a comfortable speed, to stay in the right lane and to follow the speed limit.

All participants were introduced to the setup. They each drove 5 minutes to get familiar with the driving simulator. Afterwards, they received an explanation of the text input task and were shown the different input surfaces and feedback locations. Then, they had some time (~3 min) to try out the text input system until they were comfortable with it. Next, each participant drove 5 minutes under each condition and without a tertiary task. The order of the conditions was randomized. After the driving task, qualitative information was gathered from questionnaires and short interviews. The whole experiment took about 45 minutes.

4.4.5 Results

During the experiment, we automatically recorded data on driving performance and text input speed for each participant. To evaluate the driving performance for each research condition, we statistically analyzed the data gathered from the driving simulator with Students' t-test and looked particularly at the speed and lane keeping. The participants showed similar performance in lane keeping under all conditions (see Figure 34). There were no significant differences in the measured deviation of drivers from the optimal driving lane position between any two conditions.

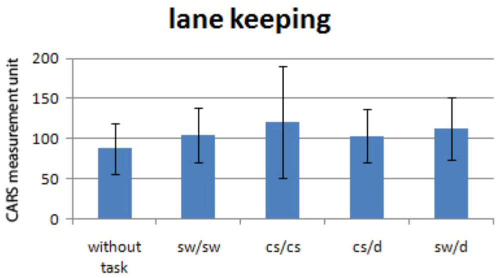


Figure 34. Mean standard deviation from the race line by condition (sw=steering wheel, cs=center stack, d=dashboard).

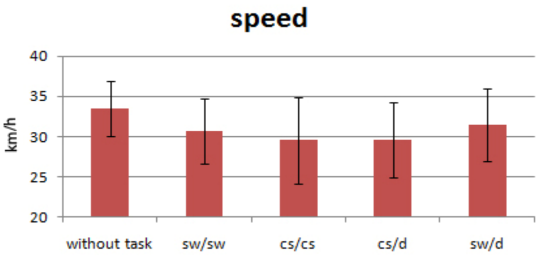


Figure 35. Average values for speed by condition. (sw=steering wheel, cs=center stack, d=dashboard).

Looking closer at driving speeds, the data shows that participants drove significantly slower while entering text compared to driving without a tertiary task (see Figure 35). Students' t-test results: (*without task, steering wheel /steering wheel*), p<0.001; (*without task, center stack/center stack*), p<0.001; *without task, steering wheel/dashboard*) p<0.001; (*without task, center stack/dashboard*), p=0.047. The conditions *steering wheel/steering wheel*, *center stack/center stack*, and *center stack/dashboard* were similar with regard to the reduction of speed: on average, the participants drove about 10% slower. The smallest effect on speed reduction (~5% slower) was observed in *steering wheel/dashboard*.

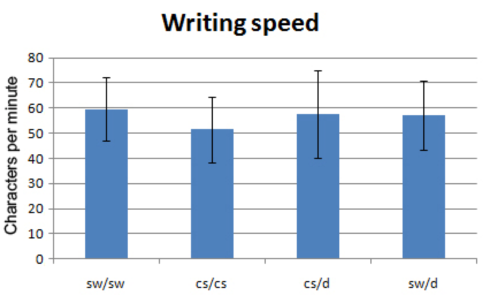


Figure 36. Average values for writing speed (sw=steering wheel, cs=center stack, d=dashboard).

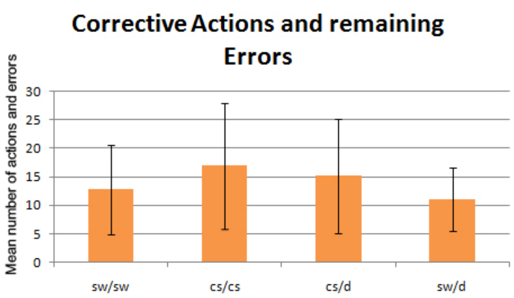


Figure 37. Average values for corrections and remaining errors (sw=steering wheel, cs=center stack, d=dashboard).

The average text input speed, the corrective actions performed while writing and the number of errors are shown in Figure 36 and Figure 37. The input speeds for all conditions where the feedback is in the driver's field of view (*steering wheel/steering wheel, steering wheel/dashboard, center stack/dashboard*) are very similar. When the visual feedback is presented in the center stack, the text input speed is on average slower; however, this effect is not significant. The number of corrections made and remaining errors are significantly smaller for entry on the steering wheel than for entry in the center stack (Student's t-test, p=0.038, comparing *steering wheel/steering wheel* and *steering wheel/dashboard* to *center stack/center stack* and *center stack/dashboard*).

In the questionnaire, we asked the participants about their preferences for the locations of the input surface and the visual feedback. 10 users selected the steering wheel as their favorite input location and 6 selected the center stack. For the location of the visual feedback the participants were equally divided (8 for the steering wheel, 8 for the dashboard). Then we asked the participants to rate on a scale from 0 to 5 how distracting they found the different conditions and how pleasant they found the interactions. The results are shown in Figure 38. The least preferred and most distracting condition was *center stack/center stack* (significantly compared to all other conditions).

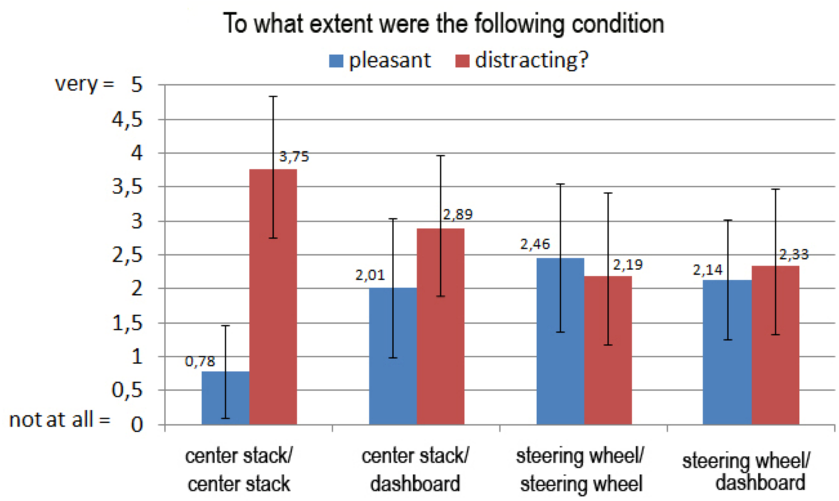


Figure 38. Subjective rating for distraction and pleasantness.

Several free-text questions asked the participants what the advantages and disadvantages of each input and output modality were. As advantages for the center stack as input surface, four participants mentioned the proximity to the gear shift, which is often used in manual-transmission cars, allowing the input surface to be reached with a familiar and regularly used hand movement. Three participants pointed out that it does not interfere with steering the car.

This is, on the other hand, the main disadvantage mentioned for steering wheel input (7 times). In contrast, the main advantage of the steering wheel as the input opportunity according to 5 subjects was that it keeps both hands at the steering wheel. As a disadvantage for center stack input, two participants listed interaction difficulties for left-handed people. Concerning the output modalities, four subjects prefer the dashboard for visual feedback, because drivers have to look at the speedometer anyway and already have the feedback in their field of view. Three participants found the output on the steering wheel positive, but didn't provide any concrete reason. Two were concerned that the driver would have to look down at the steering wheel. High similarity could be found in the answers given to disadvantages for output on the center stack. Glancing away from the road was mentioned by nine, and that it is highly distracting by seven participants. No answers to advantages of placing output on the steering wheel were given.

4.5 Discussion: Impact on Driving and Driver distraction

With the increasing number of functions that are integrated in the car for making driving more comfortable and enjoyable, the possible usage of multimodality to support this trend stepped recently into researchers' focus. The opportunity to choose a specific input device according to the driver's preferences and environmental conditions, as well as delivering output information through different channels (e.g. audio, visual and tactile), has great potential for reducing driver distraction.

Our contributions to multimodality research in the car presented in this chapter refer to input and output opportunities in the navigational context. In both case studies, we focused on the steering wheel. Since the steering wheel is one of the main input devices used while driving, it is in constant contact with the driver. As already described in chapter 3.5.2, there is an observable trend towards using input devices for tertiary tasks on the steering wheel to enable quicker driver access. We used the steering wheel for presenting navigation information using vibro-tactile output in the first case study and for inputting handwritten text in the second case study.

Our research on vibro-tactile ouput on the steering wheel showed that drivers preferred bimodal output over single modal output. The combination of vibro-tactile and visual output was the most preferred combination when compared to vibro-tactile combined with audio and audio combined with visual output. Moreover, this combination led to significantly better driving performance. Some of the participants mentioned that they only relied on tactile information and checked visual output only when they were not sure about the instruction. Due to these comments, we assume that total glance time could be also be reduced using this bimodal approach. Further tests are needed to analyze glance behavior in order to verify this statement.

One of the greatest advantages of bimodal output mentioned by participants is the aforementioned backup opportunity. In case the driver missed information on one channel, the driver can still receive the information on another channel delivering redundant information. Our initial assumption that audio output is inappropriate in this situation was confirmed by the participants before, during and after the experiments. Audio as an attention grabber was welcomed by the users but complex spoken instructions were deemed rather distracting.

Our research suggests that the current design of in-car navigational systems, where both visual and audio output are combined, is acceptable for users but inferior to the combination of visual output and embedded vibration demonstrated in our work. Our observations suggest that users rely on the vibro-tactile output as a trigger and use the visual display for confirmation and to gain additional information. The main advantage over using audio as the second modality is that vibration is unobtrusive, does not hinder ongoing conversation, and does not interfere with music or media consumption.

Overall, the design recommendation drawn from our results is to present multimodal navigational information by combining visual and tactile output. Our results found that despite using a fairly crude tactile interface, such a design can still improves the driving experience and might promote a safer driving environment.

In this experiment, the tactile interface consists of static information presented on the right and left side of the steering wheel. Varying rhythm and signal intensity can be successfully applied to provide more complex information, as shown by [Asif, Boll 2010]. With our initial experiment and an additional user study using dynamic patterns, we also found that this interface has good potential for providing navigation instructions.

In the second case study, we addressed the issue regarding right-hand and left-hand interaction in the car that consequently raise concerns about using handwriting input in the car. Burnett et al.'s [Burnett et al. 2005] results already indicate that handwriting input might be a promising option for text input in the car, but its success will depend greatly on the position of the input surface. For us, mounting the input surface on the steering wheel seems to be the most suitable position for both left-handed and right-handed drivers in both right-hand drive and left-hand drive vehicles. Furthermore, our results showed that handwriting in the center stack area and on the steering wheel have a similar negative effect on driving performance. However, our study shows that handwritten text input where drivers write on a steering wheel-mounted touchscreen with their fingers was well accepted and led to 25% fewer corrections and remaining errors compared to text input in the center stack.

Since all participants taking part in our study were right-handed, we are not able to make any statements about how left-handed users would cope. Still, considering that the steering wheel is equally accessible by both of the driver's hands, it might be worth investigating further for handwriting input opportunities. Taking participants favorite positions for receiving feedback into account (8 prefer the steering wheel and 8 the dashboard), we suggest providing multimodal feedback using both locations. This allows the driver to choose which interface he will pay attention to.

In this chapter, we focused on opportunities for multimodality in the car. We looked especially at ways to enhance the steering wheel with additional input and output devices. Our aim was to support the driver in performing tertiary tasks while keeping driver distraction to a minimum.

5 Implicit Interaction and Gaze-based Interaction to make Automotive User Interfaces more Natural

So far, nearly all input and output modalities used in the car require the driver to explicitly interact with these devices. The driver starts an interaction sequence knowingly and expects an immediate feedback from the system. One way to make automotive user interfaces more natural is the usage of implicit interaction. Implicit human computer interaction is defined as "an action performed by the user that is not primarily aimed to interact with a computerised system but which such a system understands as input." [Schmidt 2000]. This definition assumes that the system has a certain understanding of the surrounding environment and user's behavior in a given situation [Schmidt 2000].

Whenever humans communicate with each other, their eyes play an important role. If one communication partner glances consciously or unconsciously at something, the other partner might follow his gaze. Both communication partners could interpret the meaning of the glance and include this knowledge in their communication sometimes without directly talking about the topic. In HCI, sensors are often used to identify the surrounding context. To determine whether a person is gazing at an object on a screen, an eye tracker can be used. In this chapter, we present three case studies that use gaze for implicit interaction, sometimes in combination with explicit interaction. Case Study 3 deals with highlighting the last area where a user fixated on a screen before moving his attention away from the screen. This case study was presented at CHI 2011 and most parts of this case study can be also found in [Kern et al. 2010b]. In Case Study 4 gaze on a screen combined with explicit button presses on the steering wheel are used for selecting an item on the screen. This case study is also described in our paper "Making Use of Drivers' Glances onto the Screen for Explicit Gaze-Based Interaction" [Kern et al. 2010a] published at Automotive UI 2010. The last case study, Case Study 5, should enable a more natural communication in the car through a driver-passenger video link that is supported by gaze behavior. This case study was part of a Master's thesis [Tai 2009] supervised by the author. The results are presented at Mensch und Computer 2009 [Tai et al. 2009].

This chapter starts with an examination of related work in the field of implicit interaction in the car and gaze tracking as an interaction method in desktop environments as well as in the car. For all user studies conducted in the case studies, the same physical setup was used. This setup will be described in detail before reporting on the case studies and their overall findings.

5.1 Related Work on Implicit Interaction in the Car and Gaze Tracking

5.1.1 Implicit Interaction in the Car

With his dissertation “Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems” Andreas Riener [Riener 2009] provided the first contributions to the quite new research topic of implicit interaction in the car. He conducted a few driving simulations, as well as on-road studies, where he mainly used the driver’s seat for implicit input. He integrated pressure sensors into the fabric of the driver’s seat for posture recognition. His results indicate that this unobtrusive technique can be used for driver identification, as well as for predicting critical driving conditions before they occur. User tests have been planned to determine if the car seat could be also used as a universal interaction medium for implicit vehicle control, but no results have been published yet.

On the output side, Carsten and Tate [Carsten, Tate 2001] present an approach for a more natural way to force the driver to keep the speed limit. They use feedback through the accelerator pedal. When the speed limit is exceeded, the pedal becomes increasingly difficult to depress. Similarly, Gerdes and Rossetter [Gerdes, Rossetter 2001] use a gentle force through the steering wheel to encourage the driver to stay on a central position in a lane. The applied force is relatively weak and can be easily overriden by the driver when turning or changing lanes. In both examples, feedback is given in an unobtrusive and implicit way.

5.1.2 Gaze Tracking

One way to achieve implicit interaction is by tracking user’s gaze with an eye tracker. Eye tracking has been in use for more than half a century. Early work focused mainly on the application of eye tracking in the field of psychological research. More recently, it has attracted the attention of HCI researchers who have used eye-tracking data to analyze interface usability and also to interact directly with computers. The first approaches that use gaze tracking to interact with computers date back to the early 80s and 90s [Bolt 1981; Jacob 1990]. For more information about techniques and the historical background of eye tracking, see [Jacob, Karn 2003; Duchowski 2007].

In 1990, Jacob [Jacob 1990] introduced gaze-based interaction techniques, e.g. key-based and dwell-based activation, gaze-based hot spots and gaze-based context-awareness. These techniques can be used for selecting an object, moving an object, eye-controlled text scrolling, menu commands and listener windows. A lot of research in this area followed. For example, Yamato et al. [Yamato et al. 2000] and Zhai [Zhai et al. 1999] investigated a combination of gaze-based and mouse pointing. Lankford [Lankford 2000] proposed a dwell-based technique for pointing and selection including zoom functionality. Kumar et al. [Kumar et al. 2007] also used a magnification view for zooming in his “look-press-look-release action” approach. Salvucci and Anderson [Salvucci, Anderson 2000] looked into gaze-based interaction using a button for activation as an alternative to dwell-based activation. Laqua [Laqua et al. 2007] and Fono [Fono, Vertegaal 2005] focused on gaze spaces for selecting a content area or a window. Ashdown et al. [Ashdown et al. 2005] introduced pointing techniques involving a fisheye lens. Drewes and Schmidt [Drewes, Schmidt 2007] explored a different selection approach, using eye gestures. For example, looking around a dialog box clockwise meant “OK” and anti-clockwise meant “Cancel”.

All of the aforementioned projects, use explicit gaze-based interaction with the computer. The user intentionally interacts with his eyes to select something, and this selection is often combined with the explicit use of an additional device, e.g. by pressing a button. Another approach is to use gaze implicitly to enhance the user’s interaction experience. Using implicit gaze input allows the system to react or adapt better to the user, assuming that it is able to interpret the eye movement data in the context of the graphical user interface that is being presented [Rötting et al. 2009]. For example, iDict [Hyrskykari et al. 2000] offers help while reading a text in a foreign language by detecting irregularities in gazes while reading the words. The system automatically presents a translation when the user fixates on a word longer than usual. The Little Prince Storyteller [Starker, Bolt 1990] reacts to listeners’ gaze behavior on a screen that shows story-related objects. The system zoomed in on objects that got more visual attention, and the storyteller tells more about them. Further information and examples can be found in [Ohno, Hammoud 2008], which provides a comprehensive overview of gaze-based interaction.

5.1.3 Gaze-tracking in the Car

The initial use of gaze tracking in the car was in the context of fatigue detection, e.g. [Eriksson, Papanikotopoulos 1997]. This is still an ongoing topic in the research community. Eye tracking is often combined with other detection and tracking techniques, like head tracking or yawn detection [Khan, Mansoor 2008; Deng et al.

2010; Mohd Noor, Ibrahim 2010]. Usually, there are two approaches when concentrating on the human eyes: eyelid movement and gaze analysis. An overview of driver fatigue detection approaches can be found in [Wang et al. 2006; Coetzer, Hancke 2009].

Fletcher and Zelinsky used eye tracking for observation monitoring in order to detect driver inattentiveness [Fletcher, Zelinsky 2009]. Their research is based on observing typical passenger behavior. They alert the driver in case he didn't see an object in the surrounding environment, e.g. pedestrians crossing the street or a speed limit sign. They developed a system that combines obstacle detection, sign recognition and pedestrian detection with driver gaze monitoring to estimate what drivers are observing. Warnings about road events were presented to the driver when he did not look in their direction. Their study results show that the system could identify and react to road events that were almost certainly missed by the driver. However, "[d]ue to the 'looking but not seeing' case, it is not possible to determine that road events are seen for certain by the driver" [Fletcher, Zelinsky 2009]. A similar approach is followed by Ishikawa et al. [Ishikawa et al. 2004]. They combined eye tracking with head tracking using an Active Appearance Model (AAM) for detecting objects in the outside world. The "Aware" vehicle concept from Reimer et al. [Reimer et al. 2009] uses eye tracking data in addition to other physiological data to perform an overall assessment of the driver's state. One aim of this concept is to improve driving by enhancing the driver's awareness of the operating environment.

5.2 Physical Driving Simulator Setup used in Case study 3, 4 and 5

To provide a close-to-real-life car environment to the participants in our user studies, we built a mock-up of a mid-size passenger car. The car floor is formed by flat pieces of cardboard mounted on wooden crates. On this floor, we installed two front seats that can be adjusted forwards and backwards, and one backseat.

A 42" Toshiba Regaze flatscreen monitor sits on a table in front of the car seats and shows the driving simulation. Attached to the table is in front of the driver's seat is a PC racing steering wheel for navigating the virtual car through the driving environment. Pedals for accelerating and breaking are fixed on the car floor. An 8" LCD display for showing tertiary tasks and an eye tracker (Tobii X120 [@Tobii], with a data rate of 120Hz) complete our basic setup. In Figure 39, the basic setup of our driving simulator is shown. The eye tracker can be exclusively used for tracking gaze either on the small display or in the virtual environment on the big screen. In the first case, the eye tracker is placed underneath the 8” display to capture the user’s gaze (see Figure 39a). In the second case, the eye tracker is placed above the steering wheel in front of the driver such that it does not block his view of the 42” screen (see Figure 39b).

A driving simulation runs on a consumer PC and additional PCs or laptops. For dealing with the tertiary tasks, other applications can be added.

Figure 39. Physical setup of our driving simulator consisting of car seats, a 42” flatscreen, an 8” LCD display, pedals for accelerating and breaking and an eye tracker. a) Eye tracker is placed above the steering wheel in front of the driver. b) Eye tracker is placed underneath the 8” display.

The eye tracker delivers its data via a LAN connection to a PC, where the data analysis can be performed. To offer a unique and easy-to-use interface for the eye tracker, we developed an eye tracker component using the EIToolkit, described in detail in chapter 6. The EIToolkit *eyetrackerStub* is implemented in C# with the Tobi SDK [@TobiiSDK] and provides a means for calibrating and receiving data from the eye tracker. This component transforms the coordinates from the eye tracker to normalized coordinates [0,1] and transfers data to the EIToolkit’s general communication area using UDP. We normalize the coordinates so that they can be used to show gaze points on any display with any resolution. This enables the experimenter to observe gaze points during a study on any observation screen. The EIToolkit enables us to provide an application that can be run with any eye tracking hardware.

The physical setup of a driving simulator described above was used in all the following case studies, sometimes with additional input and output devices that are described in the study design of the respective user study.

5.3 Case study 3: *Gazemarks* - Gaze-Based Visual Placeholders to Ease Attention Switching

The driving task with its three sub-categorizations, as well as other tasks in work and leisure settings, requires attention switching. For example, drivers might interact with a navigation device while driving and gaze alternately at the device and the forward roadway or desktop users might search for information on a sheet of paper and then enter it into an online form. With information printed on paper, we see that people often use their fingers or other objects as placeholders to keep remember their last gaze position before looking away. Using these simple aids, the process of switching attention between displays can be simplified and sped up. Concepts like Kirsh's *entry points* [Kirsh 2001] and Dix et al.'s *triggers* and *placeholders* [Dix et al. 2002] help to structure the environment to be able to keep track of multiple activities over different timescales. A placeholder could be something as simple as keeping a finger on a line of text in a book while talking to a colleague. Here, the finger acts as a spatial index that allows the reader to quickly return to the point in the text reached before looking up at the colleague.

Technologies and information representations can enable users to strategically manipulate their environments in order to facilitate cognition and perception. Most screen-based information representations, for example, are more constrained than physical artefacts in terms of the resources they offer. Some include annotation, layers, text highlighting and cursors, but others, such as navigation systems in the car, offer little flexibility in how users can create placeholders. In the car, screens are typically positioned at a distance from the user in a landscape orientation. In this context, we predict that people will be less likely to use physical props or their hands as placeholders.

In this case study, we investigate mechanisms by which placeholders might be used to ease attention switching between displays in a working environment and between an in-car display and the forward roadway view in a driving context. First, we present a short pilot study where we investigated people's use of placeholders while sifting through information presented both on a display and on paper. Our main contribution is the concept of *Gazemarks*, a new eye-tracking technique that automatically provides visual placeholders to the user [Kern et al. 2010b]. The basic idea is to make use of the user's gaze behavior to determine where a placeholder could be beneficial. An implementation that provides automatic placeholders using eye-tracking equipment is described. Several parameters for the design of automatic visual placeholders are experimentally assessed and discussed. In the main study, the feasibility and utility of the approach is investigated.

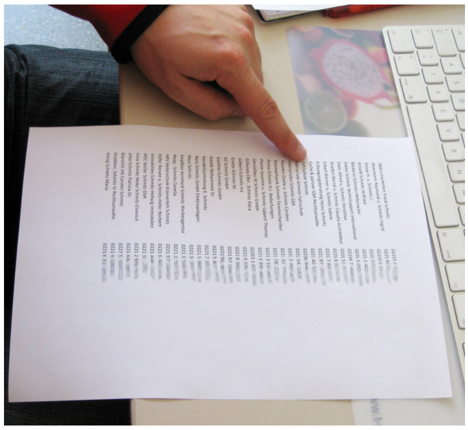


Figure 40. Driver uses his finger to mark the position on a paper map on the passenger seat (left). Finger is used as a placeholder on a paper list (right).

5.3.1 Pilot Study on the Use of Placeholders

The left picture in Figure 40 illustrates the inspiration of *Gazemarks*. The idea is based on drivers' behavior prior to the introduction of the digital navigation system. They used their fingers to mark the position on a map lying at the front passenger's seat to quickly return to a position of interest after looking away and then back to the map. A similar behavior can be observed in the complementary strategies used on paper representations [Kirsh 2001]. People use their fingers to mark their position on a list, enabling them to quickly find this place again when cross-referencing with another source of information (see Figure 40 right). To test our initial prediction of differences in these complementary actions when using physical and digital representations, we conducted an informal study in a working environment. This setting was reproducible and does not present the safety-critical issues that would arise if participants were asked to compare using *Gazemarks* on a digital map with physical placeholders on a paper map while driving. We observed participants who were asked to find and mark items on a paper list and a digital list presented on a display. Our goal was to find out whether they used any strategies to mark a position on the paper or on the digital list, and if so, what kind of strategies.

We prepared a website with a telephone list consisting of 40 names and phone numbers. The same list was also available as a paper list with 3 differences, e.g. the phone numbers for two names were switched. 30 participants (10 female, 20 male; aged 23 to 61; mean age=30.6) took part in the study. All participants sat in front of a PC or laptop at either their own desks or at the experimenter's desk. At the beginning of the study, they were asked to go to the website with the telephone list. The experimenter gave them the paper list and asked them to compare the two lists to find any differences. There was no time limit for the task. Instead, after the first difference was found by a participant, the experimenter aborted the task. By this point in time, enough information had already been obtained to determine what search techniques were being used.

Our hypothesis was that people would use fingers, pens or other objects to help keep track of where they were with the paper list.

The results of the study showed that 22 of the 30 participants used objects or fingers to mark the current line on the paper. They used only one finger (9), both a finger and a pen (7), only a pen (4), two fingers (1), or a ruler (1). Eight of these 22 participants also used a placeholder to keep track of the position on the display: the mouse cursor (5), text highlight of the name and/or number (2), or a finger (1). Three of the 30 participants only marked the last position on the monitor, i.e. by using the cursor (1), highlighting the line (1) or using the paper as a placeholder under the current line (1). Five subjects didn't use any strategy to create placeholders on the lines, neither on the paper nor on the screen. To summarize these findings: more than 5/6 of the observed participants used some kind of placeholder strategy on the paper to mark the current line, whereas only 1/3 used a placeholder strategy on the display.

5.3.2 Concept of Gazemarks

The results of the pilot study on the use of placeholders added weight to our assumption that most people would try to find something to mark their gaze position in a list when they had to switch attention between the list (physical world) and the display (digital world). This behavior can be abstracted to describe how people behave when switching attention between two different tasks.

In the following section, we introduce a method for visual placeholders called *Gazemarks*. *Gazemarks* don't require active manipulation and can therefore be controlled implicitly. Use of an eye tracker allows a system to be implemented that remembers the last gaze position on a screen after visual attention has been switched away. Upon switching attention back to the screen, the system highlights the last gaze position.

Selection of Parameters

There are three essential aspects that play an important role in the determination of the last gaze position:

- What is the definition of a gaze fixation?
- How long is the last conscious gaze fixation?
- How can showing a visual placeholder be avoided after a blink?

Gaze Fixation

The human eyes are permanently in motion albeit slight. Therefore, gaze cannot be measured as a fixation at a single pixel on a screen. A gaze on a screen is defined as a set of glances at a region with a specific radius around the first glance. That means the number of glances at this region is counted, and after reaching a set threshold, these glances are said to form a gaze. Figure 41 shows an example where a gaze can be identified (left) and another example where no gaze can be determined (right).

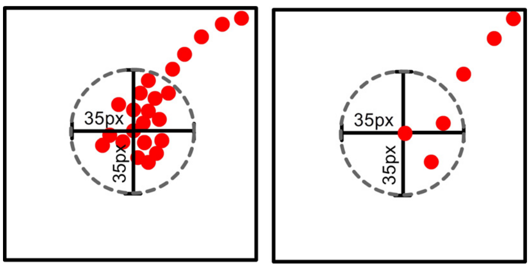


Figure 41. A gaze is defined as a specific number of glances in a predefined radius (e.g. 35px) around the first glance. The left picture demonstrates a gaze, while no gaze can be determined in the right picture.

Last Conscious Gaze Fixation

We have to distinguish between two different kinds of gaze: 1) gaze that is intentional and focus on a specific location, and 2) unconscious gaze that is too short for the user to really recognize the content at the position. The latter kind of gaze occurs, for example, when the attention switches from one task to another, and the user looks away from the display that is showing the task he is currently working on.

To avoid marking unconscious subconscious gaze positions, we performed a type of user study, called a fixation study, with 13 participants (12 male, 1 female; aged 21 to 32, mean=25.4) to find out how long the last conscious gaze fixation should be for our setup.

Figure 42. Setup of the fixation study. Participant performs a search task on an 8" display and his attention as grabbed by animal pictures on a 42".

The setup consisted of an 8" display, a 42" display and an eye tracker (see Figure 42). We used a Tobii™ eye tracker X120. The participants were asked to perform a search task on the 8" screen while animal pictures were randomly presented on the 42" screen. Participants were instructed to look at the 42" screen as soon as they recognized that a picture was being shown and to tell the experimenter which animal was in the picture. They should then continue with the search task on the 8" screen. For the search task, they were shown pictures with either 20 words or 20 digits and were asked to look for a specific word or digit. 10 different search task images were presented, and for each search image, 2 animal pictures were shown on the large display. Altogether, each participant was requested to switch her attention 20 times, resulting in 260 attention switches being recorded. These were analyzed in order to calibrate the duration of the last conscious gaze. We recorded the gazes on the 8" screen with Tobii Studio™ and determined from video analysis that the last conscious gaze has to be longer than 0.13

seconds. This value can then be used to analyze the gaze data recorded by the eye tracker and determine the last gaze position.

Blinking

Blinking is defined as the rapid closing and opening of the eyelid. On average, a blink takes approximately 0.3 to 0.4 seconds [Moses, Hart Jr 1987]. Humans are typically unaware of their own blinking. Therefore, it is necessary that blinks are ignored in the *Gazemarks* concept. Otherwise, after each blink, the last gaze position would have to be marked. To achieve this, we implemented a delay of 0.6 seconds before the last gaze position was highlighted on the screen.

Visualization Options

Many different representations could be used to mark the last gaze position on the screen. The optimal representation is probably dependent upon the task that the user is performing. While searching in a list, for example, it would make sense to mark the entire last line. However, for searching on any graphical user interface (e.g. a desktop environment or a navigation map), it makes more sense to mark a region or a point. Therefore, we decided to focus on the more generic variation.

We proposed three different visualization options:

- **Flag**: Marking a point with a flag or an arrow (see Figure 43 left)
- **Spotlight**: Marking a region by drawing a circle around the last gaze position. Outside the circle the representation is grayed out (see Figure 43 middle)
- **Soft spotlight**: Marking a region by drawing a circle around the last gaze position but, in contrast to the spotlight, using a gradient filter to illuminate seamless transition between the focus area and the non-focus area (see Figure 43 right)

Figure 43. Three possible graphical representation of the *Gazemarks* concept flag (left), spotlight (middle), soft spotlight (right).

We demonstrated the three different visual options on an 8" screen to 6 participants (1 female, 5 male, aged 21 to 32, mean=24.3) and let them vote which one they preferred and indicate why they liked or didn't like the representations. After calibrating the eye tracker to their eyes, they were presented with a map (as shown in Figure 43). The task was simply to mark positions on the screen by looking at the display, looking away and looking at the display again. After looking back at the display, the previous gaze position was marked either by the flag (Figure 43 left), the spotlight (see Figure 43 middle) or the soft spotlight (see Figure 43 right). Each type of visual *Gazemarks* was presented six times.

Afterwards, they filled out a questionnaire. In the first question, they were asked to express a preference for the three *Gazemarks* options from 1 (preferred option) to 3 (least preferred option). The results are shown in Table 8.

	voted as 1st	**voted as 2nd**	**voted as 3rd**	**average**
flag	1	1	4	2.5
spotlight	2	4	0	1.7
soft spotlight	3	1	2	1.8

Table 8. Results of users' preferences to the three visual representation (1=preferred option to 3=least preferred option). The number of votes as well as the average value is presented.

They were also asked if they liked the representation or not and to provide an explanation. The flag was liked by 2 participants, but they didn't specify why this was the case. 4 people didn't like the flag representation. The main reason given was that detecting the flag was difficult, because it was too small and not easy to distinguish from the map background. 5 participants liked the spotlight, because it provides a larger focus area that was easier to find, and they found it to be more accurate. Another advantage mentioned for the spotlight, in contrast to the flag representation, was that it doesn't hide other information on the map. One participant didn't like the spotlight, because it was too vague. The soft spotlight option was liked by 4 subjects, because the focus was clear, the representation guides the gaze automatically to the last gaze point, and a gradient filter avoids sharp edges in the representation. 2 participants didn't like this representation, because they found the grayed-out areas to be more distracting, and they were concerned that if the position indicated as the last gaze point is not correct, it would be much harder to find information in the grayed-out areas.

The results of this study indicated that just marking a single point using a flag was less acceptable to users, because it is more difficult to find, especially when the background is colorful. Marking a region around the last gaze position seems to be more promising. The last gaze position is easier to find and the users perceive this technique to be more accurate, since it is more robust against minor deviations caused by the eye tracker. Taking the disadvantages of the soft spotlight into account, we decided to select the spotlight representation in our prototype implementation. Nevertheless, the soft spotlight might also be an option, especially after adjusting the filter so that the farthest points away from the focus point are not darker than those in the spotlight example.

Taking into consideration the concern that finding information in dark areas might be harder if the last gaze is not correctly identified, we decided that *Gazemarks* should be only visible for 3 seconds at most and should disappear directly after finding the last gaze position again.

The graphical representation of the *Gazemarks* concept is shown in Figure 44. Since the system only consists of one input device (eye tracker) and one output device (display), the footprint taken up by the *Gazemarks* concept in the design space, as well as in the cockpit, is quite small. Eye trackers are not common input devices in actual cars and therefore not yet represented in our design space. We introduced a new symbol for eye tracker, which will be also used in the following descriptions.

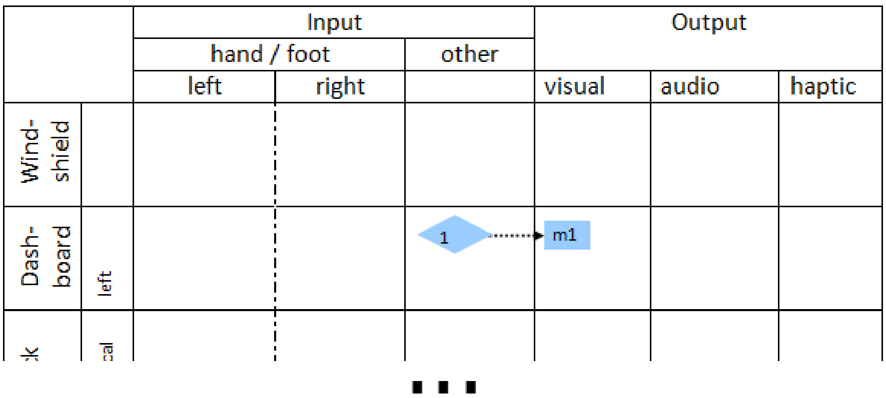


Figure 44. Representation of the *Gazemarks* concept in the design space for driver-based-automotive user interfaces. Introduction of # as new symbol for eye tracker

5.3.3 Implementation

We implemented a prototype of the *Gazemarks* concept to research if it might help users reorient themselves faster on a screen after switching attention. We chose a setting for our lab study where the user switches attention between a small display and a large screen.

Our *Gazemarks* application is implemented in Java. The application provides two mechanisms for showing the last gaze position: either on an image or using a transparent window on any screen background. The program registers with EIToolkit as a listener for eye tracking messages. It receives either valid data [0, 1], when the user looks at the display, or invalid data [-1, -1], when the user looks away from the display or blinks. Received data are collected and stored in a vector so that the last gaze position can be calculated after the program has received invalid data for 0.6 seconds. Given that eye trackers send eye-tracking data with a specific data rate, time periods can be translated into a number of received values. That means that after receiving (0.6*eye tracker frequency) invalid values, the last gaze position will be calculated. In our case, a data rate of 120Hz was used, so the calculation occurred after receiving 72 invalid values. The last gaze position is determined by examining the last valid data in reverse order. In the fixation study, we found that the duration of the last gaze position is 0.13 seconds. With a data rate of 120Hz, that means 16 values have to be in the fixation radius of a valid value. The fixation radius is set to 10% of the width of the screen resolution; this makes the program independent of the screen resolution that is used. In our case, the resolution was 600x800, resulting in a fixation radius of 80px. After indicating a fixation, this point was highlighted by the spotlight representation. To avoid distraction by marking a position that the user doesn't want to return to or by marking an incorrect position, the spotlight is only shown for 3 seconds or as long as the user doesn't look at the highlighted area. As soon as a gaze fixation is recognized in the highlighted area, it fades out in 100ms.

5.3.4 Experimental Setup

We ran a user study using the implemented prototype to compare two conditions: a control condition of performing a search task on a screen without any visual placeholders and performing a search task with *Gazemarks*. Based on the feedback from the demonstration of the visual options, we decided to use the spotlight. The hypothesis that we tested was that users would be able to perform a simple visual search task faster when the last gaze position is highlighted.

As already mentioned, the original idea for implementing *Gazemarks* came from the driving context. We therefore decided to place the participants in our driving simulator setup in our lab (see Figure 45). However, there was no driving task to perform. The steering wheel in our setup played no role in this study other than as a place for the participants to rest their hands. Since gazes on the small displays are important, we placed the eye tracker underneath the display to capture the user's gaze. The last gaze position was marked on the 8" display. We asked participants to perform an attention-switching task with a visual map searching task implemented on the small screen and a textual reasoning task presented on the large screen. We showed questions on the large display to direct participants' attention away from the small display where the searching task was performed. On the 8" screen, a map was shown with six letters randomly placed on the screen. Around each letter, eight numbers were equally spaced in a circle (see Figure 46). Two different maps were prepared to assign them in counterbalanced order for the two conditions.

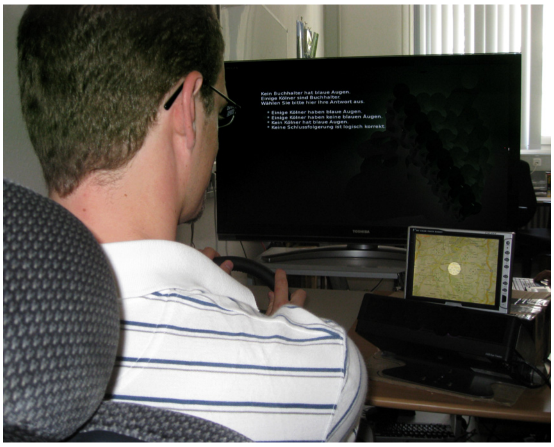


Figure 45. Experimental setup. Participant performs search tasks on the 8" display. The 42" display is used for providing questions to distract participant's attention away from the search task.

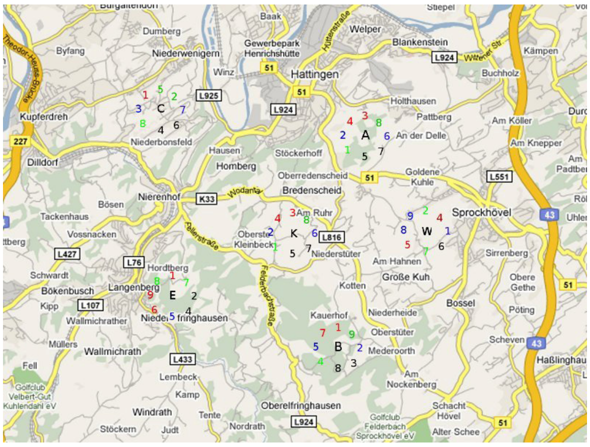


Figure 46. One of the two maps used for the search tasks.

5.3.5 Study Design and Procedure

A within-subjects design was employed, with each subject performing the task in both conditions in counterbalanced order. 16 participants took part in the study: 3 female and 13 male, aged 23 to 52 (mean=28.44). First, the eye tracker had to be calibrated to the users' eyes. Afterwards, participants were introduced to the visual search task. The goal of the search task was to find letters on a map shown on the small display (as shown in

Figure 46). The participant was initially told to find one of the letters, tell the experimenter upon finding the letter and then look away from the small display at the 42” display where two questions were shown, one after the other. After answering both questions, an arrow appeared indicating one of eight directions. The subject had to look back at the small display, find the same letter again and tell the experimenter which number is shown in the indicated direction. This procedure was then repeated for each of the six letters before switching to the other condition. The experimenter asked for the six letters in counterbalanced order. The questions displayed on the 42” screen were selected from an IQ questionnaire, so that they would be challenging enough to engage the participants’ full attention. Examples of questions asked included “What number completes the following series? 5 15 12 4 12 9?” and “Which one of these five choices complete the best analogy? Finger is to Hand as Leaf is to: a) Twig, b) Tree c) Branch, d) Blossom, e) Bark”. At the end, participants were given a questionnaire and asked to rate aspects of the *Gazemarks* concept. Further open-text explanations for their statements were collected, e.g. advantages and disadvantages of the concept, as well as demographic data. The duration of the experiment was dependent on how quickly participants answered the questions. It took between 10 and 20 minutes.

As a dependent variable, we assessed search time by measuring the time between looking back at the navigation display and finding the requested letter again. The measurement was generated automatically by starting a timer in our software after recognizing the first gaze at the 8” screen and stopping this timer as soon as a gaze was inside the area, which would match the highlighted area around the last gaze position in the spotlight condition. If the participant was not able to find the letter in 3000ms, then 3000ms was recorded for the search time indicating that the participant was not able to find the letter in time.

5.3.6 Study Results

In this section, we present and discuss the quantitative and qualitative findings of our user study.

Analysis of Search Times

As the participants’ search time had a ceiling value of 3000 ms, search times in the two conditions were compared with a non-parametric Wilcoxon signed-rank test. The median was used as a measure of central tendency; effect size is reported as Pearson’s r.

As predicted, participants were found to be considerably faster in searching for letters on the map with *Gazemarks* (Mdn=625.75 ms) than without (Mdn=1999.50 ms), $T=1$, $p<0.001$, $r=-0.87$.

Analysis of Questionnaire Results

The questionnaires asked participants to report whether they liked the spotlight representation. 15 of the 16 subjects liked the representation, explaining that this was because "the target was faster to find" (6 people); "focus leads the attention to the essential" (3 people), "it helps to orientate" (3 people) and "it reduces mental workload" (1 person). Only one participant didn't like the spotlight. He said that he didn't notice it or just ignored it.

In the next question, participants were asked to score how helpful the presented system was. They indicated their preference by crossing a line on a continuous Likert scale. The distance along the line was then measured and translated into a scale ranging from 0 (not at all helpful) to 5 (very helpful). The results showed that they typically found the spotlight helpful or very helpful (mean value: 4.09, standard deviation: 1.0). Only one participant rated helpfulness as less than 3.6. The accuracy was addressed in the following question. Participants had to score how accurate the highlighted region corresponded to their last gaze position on a scale from 0 (very inaccurate) to 5 (very accurate). The mean value was 3.24 with a standard deviation of 1.06. The accuracy depends highly on the eye tracker calibration and the movement the user carries out during the experiment, which can lead to inaccurate behavior of the system. This result also confirms our assumption that highlighting a region is more useful than marking one single point. But more consideration must be given to how we can make the system more accurate.

Participants were also asked if they found the *Gazemarks* concept to make sense in general, independent of the presented representation. They indicated their preferences on a scale from 0 (completely senseless) to 5 (very sensible). Nearly all voted *Gazemarks* as very sensible (mean value 4.26, standard deviation 0.53).

Answers given to the open questions about advantages and disadvantages also indicate the benefits that such a system might have. The main advantages suggested were saving time by allowing a search task to be performed much faster, which was mentioned by 11 participants. Three people liked that they served as a memory aid, so that they did not need to remember the last position or letter. The main disadvantage was seen as the loss of contextual information, because other important information in the greyed-out area was harder to recognize (six answers). One participant mentioned that it might get annoying after a while. Three also mentioned that the reliability has to be high to avoid them becoming distracting.

In the last section, participants were given the opportunity to suggest an alternative representation of the last gaze position. Three suggested marking only a single point with a flag, an arrow, or a pulsating point. Two indicated they would like to zoom in to the focus area, and one suggested a fisheye view. Two participants also suggested a flashing light or an animation around the last gaze position.

Marking a single point makes the potential inaccuracy of the system more obvious, as we already observed in the preliminary test. Zooming in to the focus area is counter-productive, as it also means losing context information. Blinking and flashing might be applicable in settings other than the car but could become annoying. It should not be considered for the car, since flashing animation would attract too much of the driver's attention while driving [AAM 2006; European Communities 2007].

The fisheye would be an interesting approach to highlight the last gaze position and will be considered in future work.

5.3.7 Discussion

In this case study, we have described *Gazemarks* as an approach to automatically create visual placeholders based on users' gaze. In tasks where users are required to switch their visual attention between displays, getting reoriented to the last position of interest when coming back to a display can be a problem. When using paper-based representations, people often use fingers or physical props as placeholders, facilitating reorientation when returning to focus on the representation. *Gazemarks* are designed as visual aids on digital displays to provide these placeholders automatically and hence support the user's attention switching between displays.

It remains to be seen in which contexts the *Gazemarks* concept might be of greatest use. We propose three application domains where *Gazemarks* may have a role to play:

Desktop Environment

As suggested by our pilot study, a potential benefit could be seen in work-related tasks where people have to type in information filled out in paper forms or to cross-reference paper with digital information, e.g. in an insurance company or in a university administration department, where exam results are entered into databases. *Gazemark*s could help users find the input fields on the screen faster. *Gazemark*s could also be helpful in multi-monitor setups. As Grudin [Grudin 2001] highlighted, the secondary screen is often used as a space for supporting a primary task presented on the main screen, e.g. checking lists of variables while debugging program code. *Gazemark*s could facilitate finding the desired variable quicker on the secondary screen. Furthermore, using *Gazemarks* on the primary screen would also make sense, for example, in marking the last position in the program code.

We also see a potential benefit in a normal working environment where there are many interruptions by clients or colleagues, which can require turning attention away from the screen and from the current task. After looking back to the screen, *Gazemarks* could help the user get reoriented on the screen, even in cases where the interruption takes an extended time to remember what the unfinished task was. *Gazemarks* could also be used in a single monitor setup to support task switching between multiple windows. The last gaze position on each window before minimizing it could be highlighted after maximizing it again.

Small Devices / Mobile Phones

Dickie et al. [Dickie et al. 2006] have already illustrated how to use an eye tracker with a mobile phone to handle interruptions. A video sequence or a speed-reading application is stopped as soon as the user stops looking at the screen. With our approach, the last gaze position would also be highlighted. This probably doesn't make sense in the case of a video but could support normal reading on mobile phones or browsing the Internet on small devices.

User Interfaces in Cars

The initial idea was mainly driven by the driver's physical interaction with a map in cars, which was commonly performed in the pre-navigation-system-era. This is why we considered using the *Gazemarks* concept for automotive user interfaces and will discuss its usage in the car in more detail.

The multi-tasking nature of interacting with automotive user interfaces while driving (the primary task) is obvious and unavoidable. Tertiary tasks like interacting with navigation or infotainment systems force the driver to split his attention, which consequently leads to distraction from driving. One of the main design goals for developing automotive user interfaces is interruptibility (as described in chapter 2.5). The performance of the tertiary task is continually interrupted by driving and the driver often needs a number of attention shifts to complete it [Monk et al. 2002]. The time before the driver is able to return his attention to the tertiary task again is filled with other tasks that are attention-demanding. Therefore, it can sometimes be difficult to get reoriented on the display. For example, the driver may forget his position in a list of music when searching for a title. Another important issue that was addressed by Monk et al. [Monk et al. 2002] in a user study is the point at which a task is interrupted. Interrupting in the middle of a task or when the task is nearly finished results in longer resumption periods, whereas interrupting after one subtask is completed and before the next subtask is started decreases resumption time. The latter is also true when interrupting repetitive tasks (like scrolling through a list). The interaction sequence also might influence driver's decision to interrupt a task. If a task is difficult to resume and nearly finished, a driver might be compelled to complete a task even when it may lead to a critical situation. Monk et al. [Monk et al. 2002] already made arguments on using visual and other cues for reducing attentional costs. However, they don't provide a concrete idea.

Gazemarks would help the driver remember at which point in the interaction sequence he was interrupted, thereby minimizing the time it takes to get reoriented to the screen and consequently reducing the time spent looking away from the road. On the other hand, it would probably lower the threshold for interrupting the task when the driver can be sure that resuming the task would be much quicker than without a visual hint.

Alternative *Gazemarks* representations in the car context could be used as the visual hint to the presented content on the screen. For example, when a list of music titles is shown, the last title could be highlighted, or while reading a text on the screen, the word in focus could be underlined. It remains to be seen whether changing the visual representation of *Gazemarks* according to different driving contexts or using the same representation in all contexts would be less distracting to the driver.

Navigation systems would be an interesting special case for *Gazemarks*, because the car is in motion and the visual representation of the navigation map would therefore be moving on the display as well. Highlighting the last gaze position would not make sense here and lead to confusion for the driver. Therefore, the gaze point has to be set on the moving map such that the visual placeholder is moving, too.

So far, we only focused with our user study on the stationary setup. In an earlier informal user study with two participants, we tried to find a way to evaluate the *Gazemarks* concept in the driving context. We tried using LCT [Mattes 2003] (see chapter 2.6.4) for measuring driver distraction while having participants perform the same search task as in the stationary setup. We found that LCT was not very suitable for this kind of test, because the lane changes are more or less predictable and could be quickly executed. Participants would therefore have less problems getting reoriented to the screen after completing a lane change and seemed to locate the requested number effortlessly. The participants became so well acclimated to the attention-switching task after two or three lane changes, that no measurable differences in their driving performance could be detected. Differences in search time also could not be detected, because the lane change duration was not long enough for the participants to forget where the letter was located, even in the non-*Gazemarks* condition. It seems that a more complex driving situation that demands more of the driver's attention on the primary task is necessary to evaluate the *Gazemarks* concept for tertiary tasks in the driving context.

5.4 Case study 4: Making Use of Drivers' Glances onto the Screen

In this section, we introduce an alternative approach for a "hands-free" interaction technique in the car while driving [Kern et al. 2010a]. We address the following question: Given that touchscreen interaction inherently requires the driver to look at the screen; can we exploit this glance in order to avoid the need to take one hand off the wheel? In other words, can we use implicit gaze as part of an explicit interaction? In a user study, we propose and assess a gaze-based approach that replaces the "touch" in touchscreen interaction by combing the gaze input on the screen with a button on the steering wheel (see Figure 47). We compared this new technique with existing common practices in the car: touchscreen interaction and speech recognition.

5.4.1 Proposed Gaze-based Interaction

With the proposed gaze-based interaction, all interactions the driver is able to perform with a single touch on a touchscreen can also be performed using gaze. The principal design goal with this modality was that the duration of the gazes on the screen should not be longer than that required when using touchscreens. Recent eye trackers support an update rate of 60Hz or 120Hz, which enables almost real-time feedback. These trackers can detect when a user merely glances at an item. As opposed to touch, gaze-based interaction is indirect and does not implicitly offer a means for providing feedback to the user or selecting an item on the screen.

Highlighting an Item

Providing a feedback cursor for the eye is difficult, since the calibration may not be perfect and the human eyes are permanently in at least slight motion. Therefore, we propose providing visual feedback by highlighting the item the user is looking at. This could be done by framing the item, by changing its background color or by similar mechanisms that are used in systems using a multifunctional controller. If not designed with a threshold, the highlighting might toggle too quickly between different items on the screen. In order to avoid this effect, we are using a spatial and temporal threshold before switching to the next item. We move the visual feedback only if five glances have been registered in a new area. In our case, where we have used an eye tracker with a data rate of 120Hz, this means a delay of 0.04 seconds. The temporal threshold has to be as short as possible so that the user does not become aware of this delay, and the spatial threshold has to match the minimal size for which to give feedback (in our case a single word). An interaction sequence with a multimodal display is often interrupted as the driver should regularly look back at the street again. Our system is designed to not force more or longer gazes than that required by a touchscreen. To address this issue and ease the attention-switching process, we keep the last item highlighted when the driver looks away so that he can select it without looking back at the screen, as well as orient himself faster when looking back, similar to how our *Gazemarks* concept works (see previous case study and [Kern et al. 2010b]).

Selecting an Item

There are two common ways to select an item with gaze: 1) by looking at an item in combination with pressing a button, and 2) by a dwell time approach [Jacob 1991]. The dwell time approach requires the user to look at an item for a defined time period (about 150-250ms) to select it. Though Jacob [Jacob 1991] found that the dwell time approach is more convenient, we believe that the look-and-press-button approach is more feasible in a driving condition, because the driver is not forced to look at an object longer than necessary. Therefore, we propose a push-to-select button on the steering wheel (similar to the push-to-talk button).

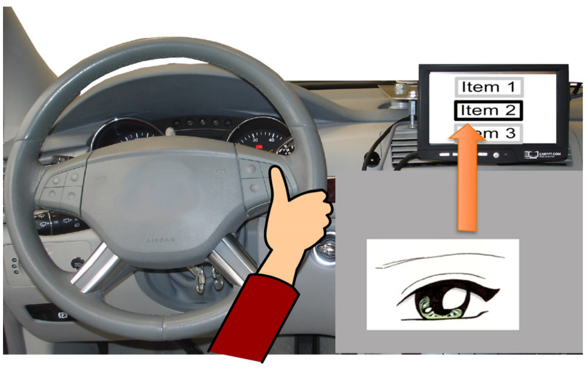


Figure 47. Proposed gaze-based interaction in the car. Driver highlights an item by looking at it and selects it by pressing the push-to-select button on the steering wheel.

5.4.2 Experimental Setup

As mentioned earlier, the proposed gaze-based interaction approach can be applied in principle in any application domain where touchscreens are used, in particular for menu item selection, list selection, item selection in a 2D space (such as points-of-interests on a map), and grid selection (rows and columns of buttons). The example studied here belongs to the category of list selection. In order to measure effects on the critical part of the interaction and to be able to control the complexity and occurrences of errors so that results are more easily reproduced, we simulated a correction task in the automotive speech recognition context. We designed an experiment to compare gaze-based interaction with touch and speech by having participants perform the task using the proposed hands-free gaze-based approach, touchscreen interaction (neither hands-free nor eyes-free) and speech interaction (hands-free).

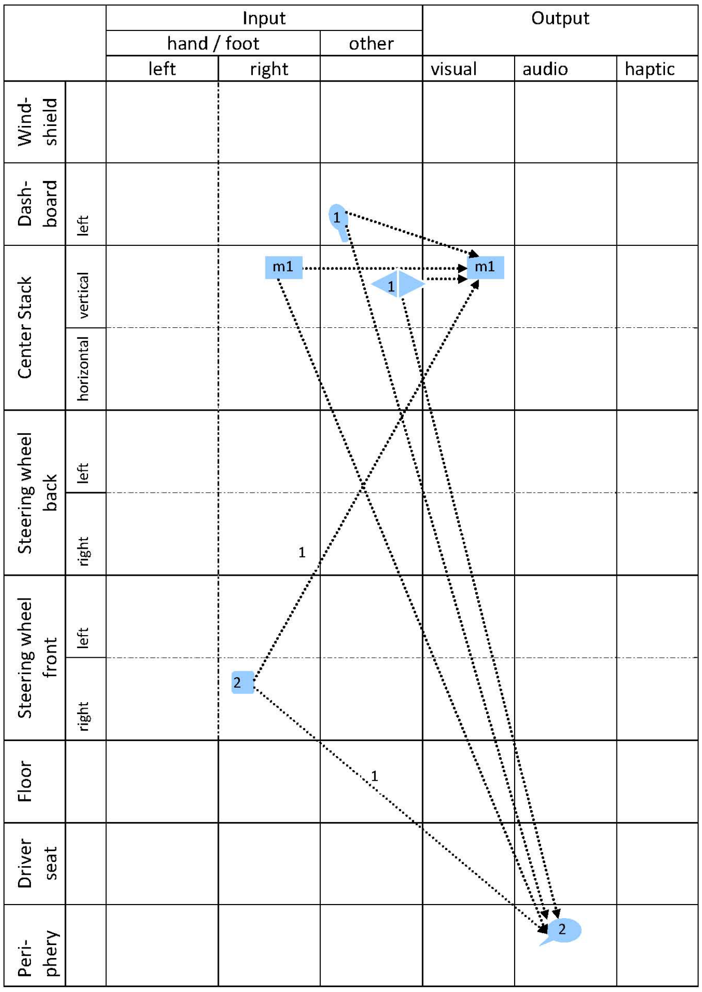


Figure 48. Representation of the three interaction options compared in our user study in the design space for driver-based automotive user interfaces.

In Figure 48, the graphical representation in the design space for driver-based automotive user interfaces of a cockpit including the three interaction techniques are shown. In the touch condition, the touchscreen is shown as an input modality and is connected with the touchscreen as output modality. Additionally, loudspeakers present audio feedback when pressing a virtual button on the touchscreen. In the speech condition, the microphone is connected with the screen and the loudspeakers presenting audio feedback. For activating speech recognition, a button on the steering wheel is needed. Pressing this button also leads to an audio feedback in case of a "bing", indicating that the driver can start speaking. The eye tracker is directly connected to the screen, and for selecting a word on the screen, a button on the steering wheel is needed. Audio feedback is only provided when a false selection has been made.

We developed a task sequence that can be iterated and therefore requires no further instructions from an experimenter during the experiment. As already mentioned, we chose a scenario in the automotive speech recognition context. Unconstrained dictation, e.g. for emails or SMSes, is the hardest form of verbal input to be processed with automatic speech recognition (ASR) and remains error-prone, especially when background noise is present or the user stumbles over his words or pauses in the middle of words because he is concentrated on driving. Since we were not interested in speech recognition itself and wanted to get comparable results, we produced a set of sentences with recognition errors and told participants that the voice recognition aspect would be simulated by a computer and that their task would start afterwards. In Figure 49, the task is illustrated. First, a computer voice read one sentence that contained an error to the participants. Then, the participant's task was to select the incorrect word. For this task, a numbered list with three alternative words appear with the fourth entry in the list being the word "delete". After selecting the correct option, the first screen with the new (or deleted) word is presented, and the participants have to select the send button. A new sentence is then displayed and the interaction sequence is repeated. To make sure that participants choose the right word for correcting only the incorrect word in the sentence and only the correct alternative can be selected. If any other option is selected, a "beep" indicates the mistake and nothing else happens.

Figure 49. Interaction sequence: After selecting the incorrect word, 4 alternatives are presented. By selecting the correct option the first sentence with the corrected word is shown. In the first row an interaction sequence for correcting an incorrect word using touch and gaze are shown. In the second row one word has to be deleted by using speech (number of the word has to be said).

We implemented the above introduced scenario with Flash ActionScript 3. For the connection to the eye tracker we utilized the EIToolkit *eyetrackerstub*. The Vista speech recognizer was used for speech input. Our driving simulator setup was additionally equipped with a microphone for the speech input. The eye tracker was placed underneath the 8" screen for recognizing driver's gazes onto the screen. Figure 50 illustrates the setup of our experiment.

5.4.3 Study Design and Procedure

For the experiment, 24 students were recruited, three of which were female. The age of subjects ranged between 21 and 32 with an average of 25.2 years. 16 of the participants drive under 10,000 km per year and 8 drive between 10,001 and 25,000 km per year. 20 subjects stated that they have a high or very high interest in modern technology.

We chose a within-subjects design where participants performed the aforementioned scenario in the following 3 conditions in counterbalanced order: TOUCH, GAZE and SPEECH. In the TOUCH condition, all operations had to be performed by touch using the touchscreen. With GAZE, subjects looked at the words to select them, which was indicated by a thin frame appearing around the word. To complete the selection, subjects had to press a designated button on the steering wheel. With SPEECH, each word in the original sentence was annotated with a superscripted number. The subject had to press the push-to-talk button on the steering wheel and say the number of the word. After a list of the alternative words and a delete option were displayed on the screen, the subject had to say the number of the list entry: "1", "2", or "3" for one of the word alternatives and "4" for delete. For the latter option, they could also say “delete” (see bottom example in Figure 49). In order to finish the interaction sequence, the subject had to say the word "send". All presented sentences were comprised of five to six words with eight to nine syllables. Two thirds of the sentences were correction cases (e.g. "Peter has tree chocolate bars” instead of “Peter has three chocolate bars”) and one third were deletion cases (e.g. "You can see trf roadworks all around" instead of “You can see roadworks all around”).

Figure 50. Experimental setup consisting of a 42“ screen showing the LCT driving simulation, an 8“ screen showing the correction tasks, an eye tracker, a steering wheel with a push-to-select button on the right side and pedals.

Driving performance while performing the correction tasks was measured with the LCT (see [Mattes, Hallén 2008] and chapter 2.6.4). Immediately after completing of the driving trial in the respective condition, the drivers were given a Driver Activity Load Index (DALI) questionnaire (see [Pauzié 2008a; Pauzié 2008b] and chapter 2.6.7). As recommended in the standard procedure, we averaged the rating scores over all 7 dimensions as a global assessment of driving task workload. The performance measures in the tertiary task were: 1) the number of sentences that could be corrected in a fixed period of time, and 2) the number of errors that were committed during that interaction.

At the beginning of the experiment, the eye tracker had to be calibrated to the user's eyes. Afterwards, the experimenter explained the correction scenario as well as the LCT driving task. The participants performed a test drive with LCT followed by the BASELINE 1 drive. Before each condition was performed, the participants were demonstrated the task sequence while driving and had a few minutes to try it out by themselves. Because eye tracker interaction was new for all participants, this trial phase usually took two to three times longer than in the other conditions. After each condition, the DALI questionnaire had to be filled out. The experiment finished with the BASELINE 2 drive, and the questionnaire asked the user about his preferences, as well as the advantages and disadvantages of each condition. The entire experiment took approximately 60 minutes.

5.4.4 Study Results

Analysis of Driving Performance Data

The LCT analysis program delivers the average deviation of the ideal line in meters for each condition and each subject (see Figure 51). A repeated measures ANOVA was carried out with the following results: the main effect of the conditions was significant ($F(4,20)=29.7$, $p<.001$), indicating that driving performance was affected by the different conditions in the experiment. Pairwise comparisons (Bonferroni corrected) revealed no significant difference between the two BASELINE conditions (n.s.), which means that there is no considerable learning effect. In both BASELINE conditions, line deviation was significantly lower than in any of the experimental conditions ($p<.001$). Accordingly, each of the tertiary task conditions resulted in decreased driving performance.

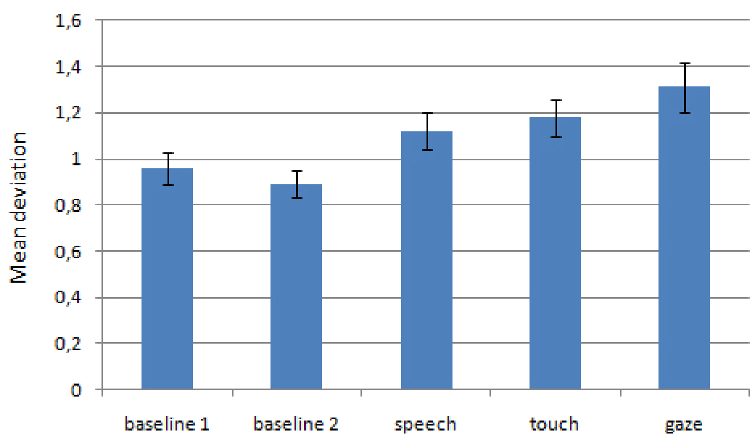


Figure 51. Deviation from the ideal line in the LCT for baselines and experimental conditions.

The SPEECH condition has the least deviation, but it did not differ significantly from the TOUCH or GAZE conditions (n.s.). However, when comparing the ideal line deviation of GAZE with TOUCH, the latter distracted subjects significantly less from driving than the former ($p<.05$).

Results of Subjective DALI Ratings

Repeated Measures ANOVA revealed that there was as a significant difference between the conditions ($F(2,22)=20.3$, $p<.001$). Helmert contrasts yielded a significantly lower overall demand for SPEECH than for TOUCH and GAZE ($F(1,23)=41.9$, $p<.001$). The comparison of TOUCH and GAZE was not significant ($F(1,23)=.19$, n.s.).

Analysis of Tertiary Tasks Completion and Errors

Since the LCT driving task was invariably conducted on tracks with the same length and speed was constantly set to 60 km/h, the available time for completing the tasks was the same for every driver and condition. For task completion (see Figure 52), a repeated measures ANOVA revealed a significant difference between the three conditions ($F(2,22)=130.9$, $p<.001$). Helmert contrasts furthermore showed that in the SPEECH condition, significantly less tasks could be completed than in the other two conditions ($F(1,23)=173.8$, $p<.001$). More tasks could be completed in the TOUCH than in the GAZE condition ($F(1,23)=18.3$, $p<.001$).

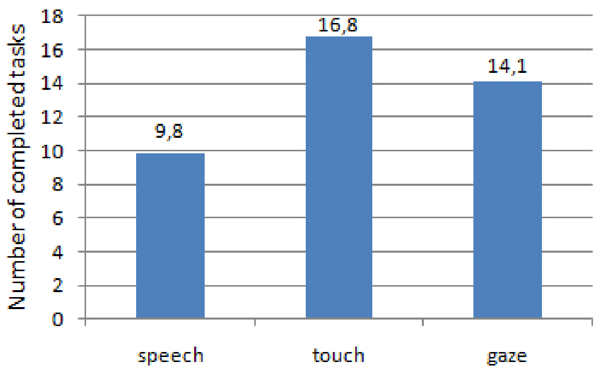


Figure 52. Average number of tasks completed during each of the driving conditions.

Another aspect one should consider is the number of errors a subject committed in a specific condition. The number of errors was registered online by the experimenter. Accordingly, the number of errors committed in relation to the number of tasks fulfilled can be compared for the three conditions. A portion of the errors can be attributed to subjects making mistakes in the judgment of which word should be corrected. However, a pretest revealed that the errors were easy to detect and evenly distributed across conditions, so this argument is rather outweighed. Also the assignment of sentences with respect to conditions was balanced. Hence, no difference in the difficulty of sentences could be held responsible for the differing error levels. The different technical states of the systems used for the conditions become most obvious here. All three conditions were compared by conducting a repeated measured ANOVA. A significant difference between the conditions could be measured ($F(2,22)=8.1$, $p<.01$). Here the GAZE condition differed significantly from the SPEECH and TOUCH conditions ($F(1,23)=12.4$, $p<.01$), revealing that more errors were committed in the GAZE condition than in the other two conditions. When comparing the TOUCH and SPEECH conditions subsequently, no significant difference in the amount of errors could be detected ($F(1,23)=.03$, n.s.).

Analysis of Questionnaire Results

In the questionnaire at the end of the experiment, participants were asked to score on a like-scale ranging from "I totally disagree"=1 to "I totally agree"=5 the following three statements:

1) It was *difficult* to perform the correction tasks under condition X.
2) Performing correction task under condition X *distracts* from driving.
3) Especially *useful* while driving was condition X.

Mean average values of the answers to these questions are shown in Figure 53.

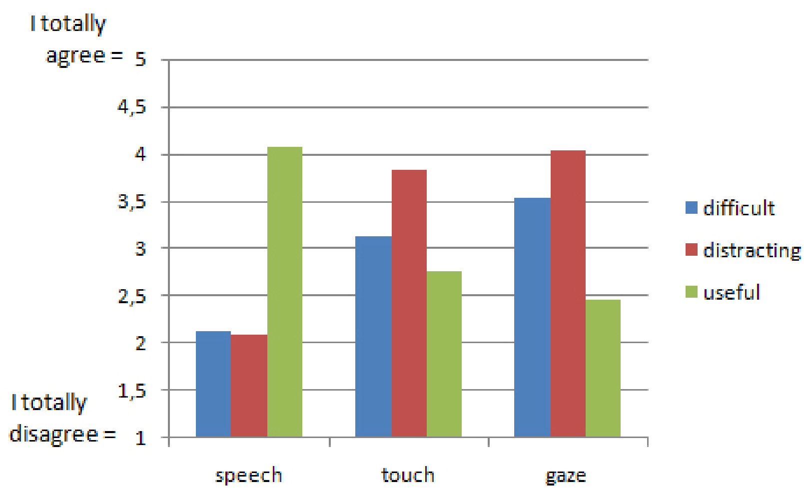


Figure 53. Mean score values to the statements: 1) It was *difficult* to perform the correction tasks under condition X. 2) Performing correction task under condition X *distracts* from driving. 3) Especially *useful* while driving was condition X.

Speech was voted as the least difficult, least distracting and the most useful input opportunity, whereas gaze input seems to be rather difficult, distracting and less useful. Voting results for touch interaction was in between these two conditions. Furthermore, participants were asked to decide if each condition is: time-saving, interesting, precise, stress-free, comfortable and intuitive (see Table 9). Speech input is considered to be time-saving by 15 participants, stress-free by 19 persons, comfortable by 17 participants and intuitive by 16 participants. Gaze-based interaction only wins in the category interesting (said by 20 persons). Touch seems to be the most precise method (said by 16 participants).

	time-saving	interesting	precise	stress-free	comfortable	intuitive
speech	15	7	9	19	17	16
touch	8	2	16	5	6	16
gaze	7	20	7	4	8	9

Table 9. Number of answers given to the question: "Which condition [speech, touch, gaze] is [time-saving, interesting, precise, stress-free, comfortable, intuitive]?" Multiple answers were possible.

With open questions, we asked for advantages and disadvantages of each condition. Five persons said that speech input is easy to use and that it results in less distraction. Another five liked the fact that only short glances on the screen are needed for complete the task sequences. A further advantage that was seen by three participants is that the hands remain on the steering wheel. On the other side, recognition errors were stated as a big problem from ten persons. Three didn't like having to press the push-to-talk button before they could speak. Two stated that the mapping between words and numbers was not intuitive. Advantages of touch input were precise selection (8), intuitiveness (5) and simplicity (4). In contrast, the position of the display required body movement, and that was stated as the main disadvantage for touch input by six participants. Three others disliked that they had to remove their hands from the steering wheel, and two criticized the long gazes away from the street. Gaze-based interaction requires less body movement (5), and the hands could remain on the steering wheel (5). Five participants found the interaction to be very precise. On the other hand, two people criticized that this interaction technique was not precise enough. Five people found that they had to gaze for too long at the screen to complete the tasks, and three would prefer using periphery viewing instead.

5.4.5 Discussion

We presented a "hands-free" interaction technique based on driver's gazes. This interaction technique seems to have interesting properties for car user interfaces, since drivers can operate it while keeping their hands on the steering wheel and do not need to have the screen placed within their reach. Initially, we thought we could take advantage of the driver's natural glances at the screen to receive information for a more implicit and natural form of interaction while driving. However, observations and participants' feedback indicate that selecting a word by gaze (at least in the form prescribed in our experiment) is more demanding and requires more explicit interaction from some users than necessary. Periphery viewing, which they preferred using in the other conditions, was not possible, because the eyes would not be recognized properly by the eye tracker. In the TOUCH condition, most tasks could be easily performed by the subjects, probably because this interaction technique is well-known. Even thought there were no significant differences measured regarding driving performance in the speech condition compared to the other conditions, participants performed best in the speech condition. Answers given in the questionnaire also showed that participants found the speech condition to be the least distracting, least difficult and most useful opportunity.

When interpreting the results of the user study, it should be taken into consideration that while touchscreens are a familiar and well-established form of interaction with a simple technical realization, gaze-based interaction is completely unfamiliar and requires a rather complex technical setup. Research on speech-based interaction had to deal with similar problems a decade or more age: speech interaction was unfamiliar to most people and the recognition rate was low. For experiments on speech interaction, a wizard-of-oz setup could be used to eliminate the impact of technical insufficiencies. The wizard-of-oz setup, however, cannot be applied to gaze-based interaction, because reliably following the gaze of the subject manually in real-time and with high accuracy is not feasible. Interest in this kind of interaction was stated by almost all participants. This experiment was the first of its kind and maybe with a more stable setup that supports gaze recognition from periphery glances at the screen, the results of our user study might be different.

5.5 Case study 5: Supporting Face-to-face Communication in the Car

Communication in the car while driving is far from being natural. Since the driver has to concentrate on the driving and usually looks forward on the roadway, he misses out on a great range of visual cues that enhance human communication or change the meaning of what was said, e.g. body language, facial expressions, eye contact and gestures. The human desire to make eye contact while communicating in the car often leads to drivers turning their head to glance at the communication partner, making them temporarily blind to the driving situation. This might be one reason why driver-passenger interactions were identified as a major source of driver distraction [Dingus et al. 2006]. There are some strategies to avoid turning the head. Some drivers adjust the rear-view mirror so that they are able to glance quickly at backseat passengers while keeping the forward roadway in their periphery view. This strategy, however, causes the driver to see less of the traffic situation behind the car. To address this problem, there are mirrors available on the market that can be installed additionally in the car to enable a line of sight to backseat passengers without losing the rear traffic view. Inspired by these mirror approaches, we designed and developed a video communication system that allows drivers to see passengers without turning their head [Tai et al. 2009]. We assume that this system enables a more natural communication in the car without negatively affecting driving performance. We present the concept along with a requirements analysis through an online survey, the prototype and a user study.

5.5.1 Concept of a Driver-passenger Video Link

To accommodate drivers who want to look at communication partners in the car while driving, we propose an approach similar to video conference systems that provides visual contact between users who are unable to communicate face-to-face. Modern cars provide different display options in the driver's field of view. Displays for rear-seat passengers are often mounted on the back of a front passenger seat's headrest.

Our concept includes webcams recording drivers and passengers' faces and displays for presenting video images of the communication partners to each other. The driver was shown video images of each passenger, preferably of the rear-seat passenger on a display in his forward field of view. If more than one passenger is present in the car, we suggest splitting the screen in two or more areas, each showing one communication partner. In Figure 54, a possible system setup is shown. Two display opportunities for driver's display are illustrated: a head-up display (HUD) and a monitor mounted in the vertical center stack.

Figure 54. Concept of a driver-passenger video link. Driver gets shown a video image of the rear-seat passenger either on a monitor mounted at the vertical center stack or in a Head-up display. The rear-seat passenger sees on a monitor in front of him a video image from the driver.

We conducted an online survey to gain some insight on how drivers generally behave while communicating with passengers and how drivers feel about having a video link system in the car that supports the communication with passengers. The survey was online over a two-and-a-half-week period and 132 people (41% female, 59% male) took the survey, 64% of them mainly drive in Germany and 30% drive in the US. They ranged from 18 to 73 (mean=34.5) in age. 72.7% of all participants drive at least some (>20%) of the time with passengers. All participants indicated that they tend to engage in casual conversation when driving with passengers. Furthermore, 60.6% plan activities and 65.9% attempt to navigate to a destination with other passengers while driving. Some (18.2%) tend to engage in heated arguments and 16.7% check up on passengers on the backseat. Almost half of the respondents indicated that they prefer having eye contact when casually conversing with passengers while driving. Regarding participants' gaze preferences with the rear-seat passenger while driving, we found the following results: most participants try to keep their eyes on the road (95%) but also use the rear-view mirror to look at them (93%), while about half would be willing to turn their heads and glance briefly at the rear-seat passengers.

In the online survey, our video link proposal was described and people were asked about their attitudes. Results can be found in Figure 55.

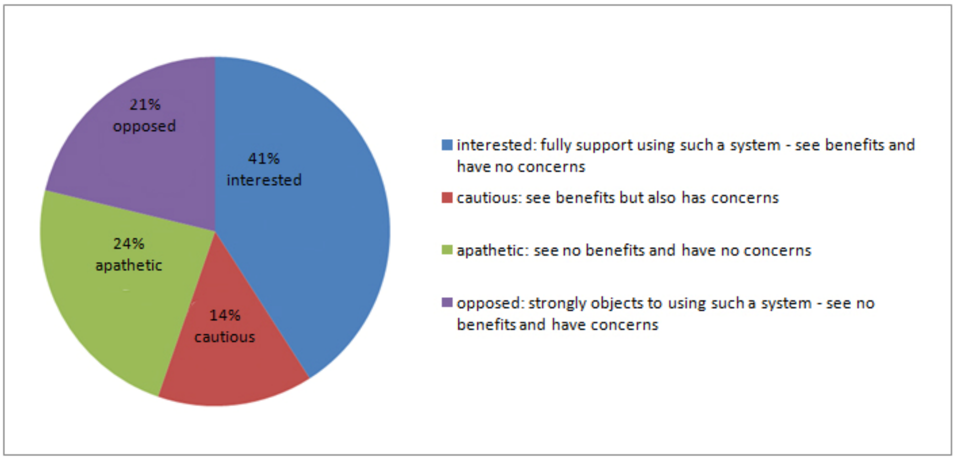


Figure 55. Online survey results: attitudes towards in-car video communication system.

The results of the online survey indicate that there is some interest in using such a system and that drivers like to have eye contact. Nevertheless, participants' attitudes towards a video link system are quite diverse. For some of them, such a system would be "too distracting" and for others, it would be "less distracting" and help keep their eyes on the road. To find qualitative results on how distracting such a video link concept is, we built a prototype and performed a driving simulator user study.

5.5.2 Prototype

Our prototype mainly consists of two webcams and two 8" displays. We focused on presenting a video image of one rear-seat passenger to the driver. This rear-seat passenger is also shown a video image of the driver. We used a laptop to transfer the video image from the webcam to the respective display for each video link. For the placement of the display to the driver, we considered two common display placements in modern cars: the vertical center stack and the windshield (using a HUD). This also offers a means for researching two different output opportunities, presenting the video image on a standard display and showing the video image in a HUD in the user's field of view. We assumed having the video image always visible in the HUD would be annoying over time and therefore decided to dim the video image when it was not needed. To avoid explicit interaction through pressing a button or using a speech command to activate the video image, we propose a gaze-aware interaction that requires minimal effort from the driver. When the driver looks at the HUD, the video image is clearly visible but never fully blocks driver's view. If the driver does not look at the HUD, the video image's transparency is reduced to 10%, resulting in a much dimmer

HUD image. We assume that this interaction enables a visual awareness without becoming a great distraction to the driver (see Figure 56). For programming this interaction, again the EIToolkit *eyetrackerstub* is utilized.

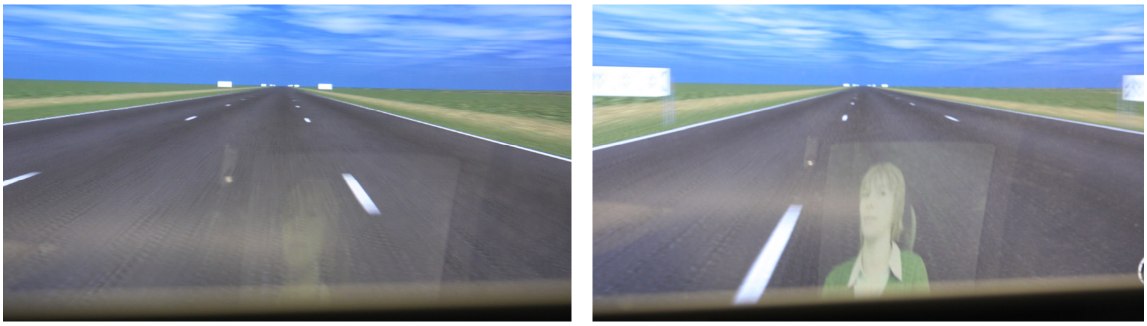


Figure 56. HUD video of rear-seat passenger in the Not Viewed (left) and Viewed (right) states.

In Figure 57, the representation of our proposed driver-passenger video link system with the two placement options for the display is shown in the design space for driver-based automotive user interfaces. Since video cameras were not yet considered as explicit input devices in the car, new symbols are introduced. Since the design space is driver-based, the camera and the display for the rear-seat passenger to view the driver are not included.

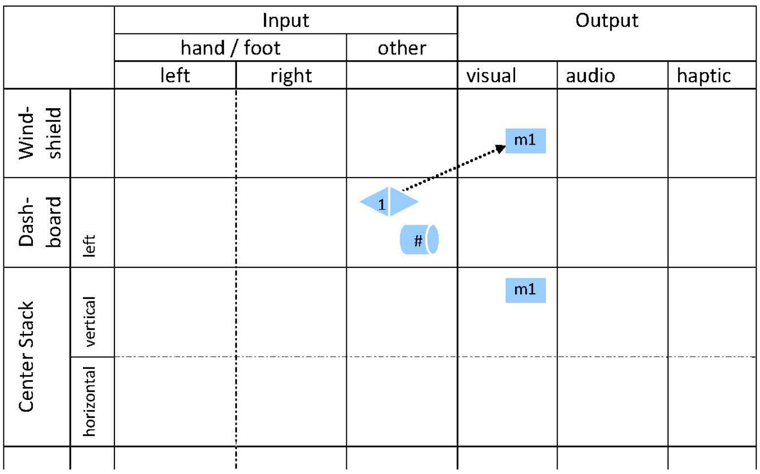


Figure 57. Driver-passenger video link representation in the design space of driver-based automotive user interfaces. Introduction of  as a new symbol for camera.

5.5.3 Experimental Setup

We designed and performed a user study to find answers to the following research questions:

1. Does a driver-passenger video-link system have a positive effect on the communication between the driver and the rear-seat passenger?
2. Does the proposed system have an effect on driving performance?
3. Are there differences in the two visualization modes – HUD and monitor?

The setup for the user study is shown in Figure 58. Our driving simulator setup was additionally equipped with a plexiglass windshield showing the head-up image (mirrored image from an 8” display). One webcam recorded the driver’s face and this recording is presented on an 8” screen mounted on the back of the front seat passenger’s headrest in the field of view of the rear-seat passenger. Above this screen, another webcam is pointed at the passenger. This video image is shown either on the 8” display to the right of the steering wheel or in the HUD projected in the bottom-middle of the plexiglass windshield, not directly in the driver’s field of view. The eye tracker stands above the steering wheel to be able to detect glances onto the HUD area.

Figure 58. Experimental setup consisting of a 42“ screen showing the LCT driving simulation, an 8“ screen showing video image of the rear-seat passenger to the driver, another 8” screen showing video image of the driver to the rear seat passenger, an eye tracker, placed above the steering wheel, a webcam facing to the driver, another webcam facing to the rear-seat passenger, a steering wheel and pedals.

The study was performed with one participant driving a virtual car in the driving environment and two passengers, one sat next to the driver on the front passenger seat and the other one sat on the backseat. Both passengers took part in all experiments.

5.5.4 Study Design and Procedure

16 participants (8 female, 8 male) were recruited for our user study. They ranged from 20 to 29 (mean=24.3) in age. All have a driver license for on average 5.8 years. Half of the participants drive weekly and 65% drive regularly but not every week with passengers. Participants got 10€ for participating in the experiment.

We chose a within-subject design experiment with the video system as our independent variable. For the video system, we have three conditions: *no video system*, *monitor video system* and *HUD video system*. We chose two different conversation tasks to have more diversity in the kind of conversation. In the *article* task, the passenger on the backseat read a newspaper article out loud, and afterwards, the driver and all passengers should discuss the article's topic. In the *game* task, the driver and passengers play the game "Who Am I?". The passenger on the backseat is given a set of cards, each with the name of a famous identity (e.g. Harry Potter or Michael Jackson). The passenger picks one of these cards, and the driver and co-driver alternated in asking "Yes or No" questions until they can correctly guess the identity. This task made sure that the driver is actually engaged in the conversation, whereas in the *article* task he was able take a more passive role.

We let participants drive twice under each condition, once performing the article task and once the game task. As dependent variables, we measured driving performance using the lane change test software (see [Mattes 2003] and chapter 2.6.4) and eye glance behavior.

At the beginning of the experiment, participants had to fill out a background form. Afterwards, the LCT driving task was demonstrated to them, after which they could try it out by themselves. Before the eye tracker was calibrated on the participants' eyes, they performed a baseline drive. The two passengers were introduced and they had time to chat for a few minutes. This conversation was recorded on video for later analyzing participants' conversation behavior without any driving task. Afterwards, each participant performed 6 drives (two for each condition) in counterbalanced order to avoid learning effects. Each drive took 3 minutes. Before driving with the *HUD video system* conditions, the experimenter explained how to activate the HUD image by gaze-based interaction. At the end, participants filled out a feedback form. The whole experiment took about 45 minutes and was recorded on video for later analyzing gaze behavior.

5.5.5 Study Results

Analysis of Driving Performance Data

Technical problems led to an exclusion of data collected from 2 participants. Therefore, the following results are based on data from 14 instead of 16 experiments. A repeated measures ANOVA was performed to determine the effect of the video system on average deviation. The condition *HUD video system* led to the lowest mean deviation while the *Monitor video system* resulted in the highest mean deviation. The mean deviation of the baseline drive was in between the two experimental conditions. However, these differences were not significant ($F(2,12)<1$, *n.s.*) (see Figure 59).

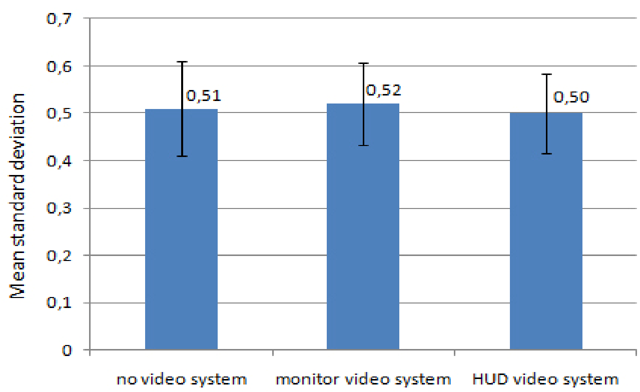


Figure 59. LCT results for average deviation in all driving conditions.

Analysis of Gaze Behavior

For analyzing the gaze behavior, the screen showing the roadway was divided into two areas: HUD area and the rest of the screen. The HUD area covers 24% of the whole screen and is located at the middle of the bottom of the screen. Furthermore, we differentiate between glances (≤ 2 seconds) and looks (> 2 seconds). Looks longer than 2 seconds greatly increase the risk of an accident [Dingus et al. 2006]. Looks and glances at the passengers and the monitor were analyzed based on the video footage. Eye tracking data were used for analyzing looks and glances onto the HUD area, and the overall driving environment on the screen. Due to technical problems with the eye tracker, data from 2 participants had to be excluded from the analysis of looking at the screen and the HUD area. All results regarding gaze-related data can be seen in Table 10.

		Reference (No driving) Mean	No Video System Mean	Monitor Video System Mean	HUD Video System Mean
At Rear-seat Passenger	#glances/min	3.5	0.1	0.0	0.0
	#looks/min	1.4	0.0	0.0	0.0
At Monitor Display	#glances/min	-	-	4.1	-
	#looks/min	-	-	0.0	-
At HUD Area	#fixation/min	-	13.9	12.4	19.3
	fixation length/min (seconds)	-	3.3	3.0	5.6
At Rest of Forward Roadway (Not HUD Area)	#fixation/min	-	74.6	73.0	73.0
	fixation length/min (seconds)	-	29.2	30.4	27.4

Table 10. Gaze behavior from video analysis and eye tracking by Video System.

Reference values are taken from the conversation that took place before the driving task started. There is a significant different between the reference condition and all other conditions. Under all driving conditions no looks at the passengers were performed and glances at the passengers were reduced to a minimum. That indicates that while sitting in the car but not actively driving, drivers preferred to have eye contact while talking with the passengers, but while driving, they minimized eye contact and attended to the forward roadway. In the video condition, drivers never turned to see the rear-seat passenger. Glances to the monitor display and the HUD video, however, indicated that participants make use of the video system to have visual contact with the rear-seat passengers. Short glances at the monitor were, in particular, often observed.

Looking closer at the two video conditions, it is conspicuous that drivers had much greater visual contact with the rear-seat passenger than when no video system was present. However, in the *HUD video system* condition, they fixated more often on the HUD area than the monitor in the *monitor video system* condition. Furthermore, they spent more overall time looking at the HUD area when the HUD video system was present. Two-way repeated measured ANOVAs performed on fixation length/min at HUD found a significant effect due to the Video System, $p<.05$. However, post-hoc tests showed that there was no significant difference between the *no video system* condition and the *HUD video system* condition. This indicates that drivers were not staring at the HUD area for long periods of times when the video image was clearly visible but instead glancing quickly at the HUD area to check on the rear-seat passenger.

Questionnaire Results

The participants were asked about their current preferences while talking with passengers. 9 of 16 preferred visual contact with the rear-seat passengers. They often use the rear-view mirror and quick head turns to look at them. On a 5-point Likert scale, participants should rank how difficult it was to drive with no video system, monitor video system and the HUD video system. They found driving with a video system significantly more difficult than driving without a video system. However, the average value of difficulty was in the middle of the scale (without video 1.3, monitor video system 2.7 and HUD video system 2.6). When asked which system they preferred, 9 participants chose conversing without any technical support, 4 chose the HUD video system and 3 the monitor system. 11 participants liked the gaze-based interaction, and 8 said that they would probably use a similar system to the HUD video system in the future.

5.5.6 Discussion

The results of the user study presented here on a driver-passenger video-link system to enable face-to-face communication in the car give some insights to answer the three research questions.

1. Does a driver-passenger video-link system have an effect on driving performance?

With the LCT, neither positive nor negative effects on driving performance could be determined. In all three conditions (*monitor video system*, *HUD video system*, *no video system*), participants performed the driving task in a similar way. It can be concluded, that the video system does not affect driving performance negatively.

2. Does a driver-passenger video-link system have a positive effect on the communication between the driver and the rear-seat passenger?

Analyses of the gaze data clearly show that the driver used the systems. They looked significantly more often at the monitor and the HUD area in both conditions compared to the reference drive without any technical support. No head turns were performed in the *monitor video system* and *HUD video system* conditions, however, in the *reference* condition, only 3 participants turned their head to look at the backseat passenger. Two did this once and one did it 4 times. Answers given to the questionnaire indicate that at least 7 of 16 participants prefer using a video system while conversing with passengers. Quantitative measures to answer this question might be difficult or even impossible.

3. Are there differences in the two visualization modes – HUD and monitor?

Participants performed best in the *HUD video system* condition. However, this effect is not significant. Participants looked more often at the HUD area in the *HUD video system* condition than on the monitor in the *monitor video system* condition. Furthermore, they looked significantly more often and for longer time periods at the HUD area in the *HUD video system* condition, indicating that they actually used the system. Subjective opinions support the impression that the *HUD video system* seems to be more useful. 8 said that they would use a similar system in the future.

The proposed driver-passenger video link system addresses the desire to have eye contact with communication partners in the car. We recognize that visual contact even in the car is a natural element of human communication, and even though there are quite diverse opinions about the usefulness of such a system, it seems to be considered useful by at least half of the participants in our online survey. In our user study, the system also provided a way to make the communication in the car more natural.

5.6 Discussion: Impact on Driving and Driver Distraction

Up until now, gaze behavior in the car has only been used for observation monitoring. In this chapter, we show the potential for using gaze tracking as a more implicit input method, which we assume can make interaction in the car be more natural. In case study 3, gaze was used to ease attention switching through automatic placeholders. Even though we cannot provide any results gained through a driving simulation study or a test track trial, we speculate that the *Gazemarks* concept would be of great benefit for the driver. In a stationary situation, users were about 3 times faster in a search task than without any support. We hope that similar results can be achieved in a driving context. Reducing the reallocation time for a task in the car leads to less interaction time and should ideally lead to less driver distraction. Further studies are needed to confirm this statement and especially to show if drivers would actually use such a system or become annoyed by it.

Results from case study 4 indicate that using gaze in combination with explicit input (in our case pressing a button) is not as natural and implicit as we previously thought. Selecting an item with gaze is more demanding than just quickly glancing at it and thereby leads to higher driver distraction. It is likely that hand-eye coordination plays an essential role here, making this input opportunity more difficult than expected.

Furthermore, a robust and precise system with high accuracy is needed. Some of the participants found the system very precise and could therefore see benefits in using such a system, whereas others stated that the system was not precise enough and might become too distracting and therefore would not want to use such a system. Speech input was preferred by the participants, because it was considered to help save time, even though participants completed fewer tasks in this condition compared to other conditions. Driving performance was also the best in this condition.

In case study 5, we introduced a driver-passenger video link system to enable more natural communication in the car between the driver and rear-seat passengers. Results of our performed user study show that participants used the systems with neither positive nor negative significant effects on driving performance. Such systems seem to enhance user experience for people who like interacting through the video link, which was less than half of our participants. The gaze-based interaction in the HUD video system condition was well accepted by the participants (11 out of 16 liked it), and we guess that it might also be useful for showing other visual information to the driver, e.g. for navigation instruction.

6 Development Support for Novel Automotive User Interfaces

In all user studies performed in the reported case studies, an effect of interacting with automotive user interfaces on driving performance could be observed and measured. Some of the user interfaces have more influence on driving performance than others. Clearly, driver distraction is the central point that has to be considered while developing new automotive user interfaces. Introducing a new user interface to the market that is not sufficiently tested against driver distraction may have fatal consequences. Driver distraction is closely associated with usability and joy of use. If the user interface is very easy to use, driver distraction should be lower than when he has difficulties to achieve his goal.

Taking up the human-centred design process according to ISO 9241-210 [ISO 9241-210:2010] which was already introduced in chapter 1 we developed in the context of the presented dissertation methods that should support this process in the automotive user interface field. The methods and their placement in the design process are shown in green boxes in Figure 60.

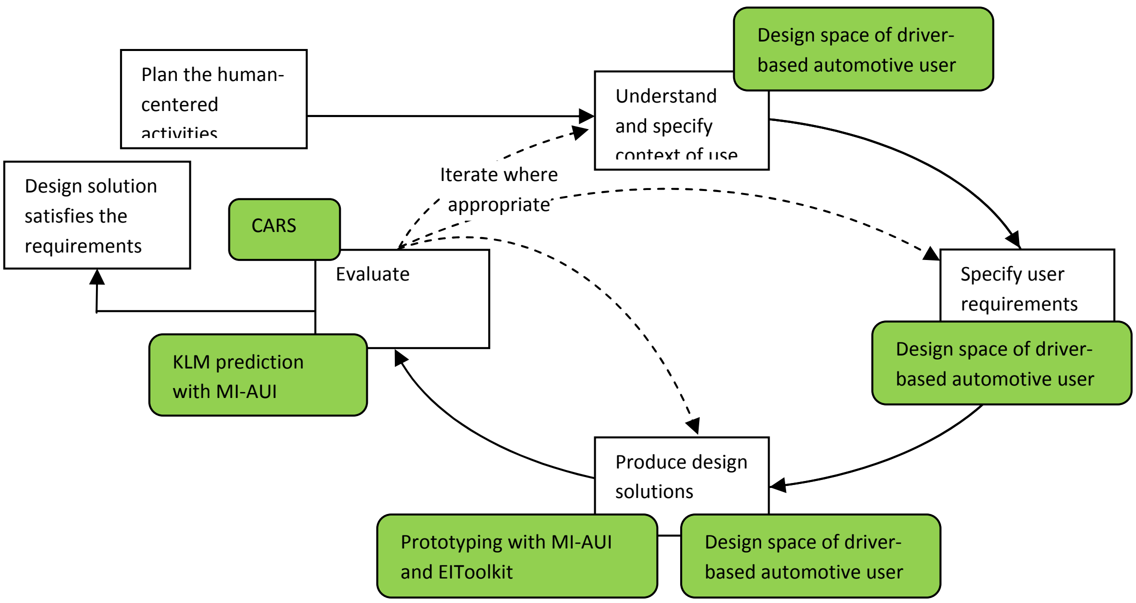


Figure 60. Human-centred design process according to ISO 9241-210 [ISO 9241-210:2010]. The green boxes placed at the respective process activity indicate where methods developed in the context of this dissertation can support the design process for automotive user interfaces.

After a short overview of related work in developing support of automotive user interfaces, an explanation of how the design space of driver-based automotive user interfaces can support the understanding of user's context and how it can help to produce design solutions will be presented. Afterwards, the prototyping toolkit MI-AUI (Modeling interaction with automotive user interfaces) will be introduced, and the usage of the EIToolkit for rapid prototyping of automotive user interfaces will be discussed. Finally, the driving simulation software CARS (Configurable automotive research simulator) [Kern, Schneegaß 2009] will be presented.

6.1 Related Work on Development Support for Ubiquitous Computing and for Automotive User Interfaces

6.1.1 Developing Support for Ubiquitous Computing Application

There are several projects and products that aim to support the development process of ubiquitous computing applications in general and prototyping in particular. We would like to refer to Paul Holleis's dissertation [Holleis 2009] for a comprehensive overview of the extensive options for rapid application development support in the field of ubiquitous computing. At this point, only two toolkits – EIToolkit and VoodooIO – will be introduced, because we used them in some of our projects.

EIToolkit – Embedded Interaction Toolkit

The EIToolkit supports the developing process of ubiquitous computing systems where heterogeneous hardware devices are often used to provide input to an application as well as present output from an application. Small proxy-like components, called stubs, exchange messages over a general communication area via UDP. The main idea is to provide a common basis for communication independent of a specific programming language but with a specific protocol. Only a small additional layer of software is required to connect a specific hardware or software to the toolkit. For example, a light sensor should be connected to an application for changing the background image on a screen depending on if it is dark or bright in the room. For using sensor information in the application, the developer only has to write a small software program that reads data from a sensor, e.g. over serial line, and transfers them into an EIToolkit message, which is sent to the common communication area. The application that wants to change the background image listens to messages in the communication area, receives the message and changes the image according to the lighting conditions.

The usage of stubs allows hardware components to be replaced without changing anything in the application logic. For our example, that means the application might also react to sound in the room in the same way. The system architecture with three example stubs is shown in Figure 61.

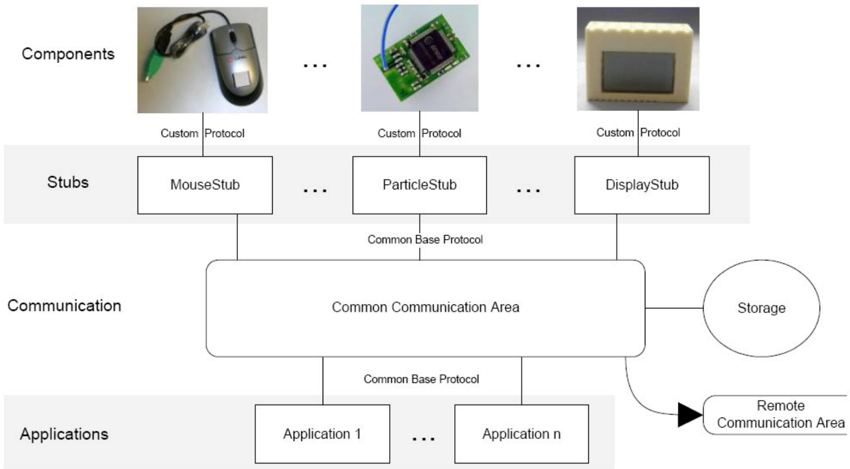


Figure 61. EIToolkit's system architecture [Holleis 2009].

So far, EIToolkit's core parts are implemented in Java, C++ and C#. Templates and scripts are provided for easily creating new stubs in these programming languages. Furthermore, libraries exist that simplify the use of communication listeners and senders. Messages are sent in the form of packets. Each packet contains the following information: who sent the packet, the type of message, the message itself and the desired receiver (optional).

The main benefits of this toolkit are that different hardware and software platforms, as well as programming languages, can be used and that the stub concept allows hardware components to be replaced without changing anything in the application logic.

VoodooIO

VoodooIO, invented by [Villar, Gellersen 2007], is an application development platform for rapid development of flexible tangible user interfaces. It consists of a malleable surface called *substrate* and a set of basic control units like buttons, knobs and sliders. The substrate is 10mm thick and can be cut into any shape so that it can be applied to existing surfaces or attached to objects. It has a built-in conductive layer that allows the control units to be placed at any location on the surface. The control units have small sharp pin connectors at their base. By pushing these pins into the surface, an electrical connection with the conductive layer is established, and the control units become part of the system. Information about appearance and disappearance, as well as the current state of the control units, is transferred via an attached USB connector to a PC. By mapping inputs to simulated keystrokes, existing software applications can easily be controlled by the tangible control units.

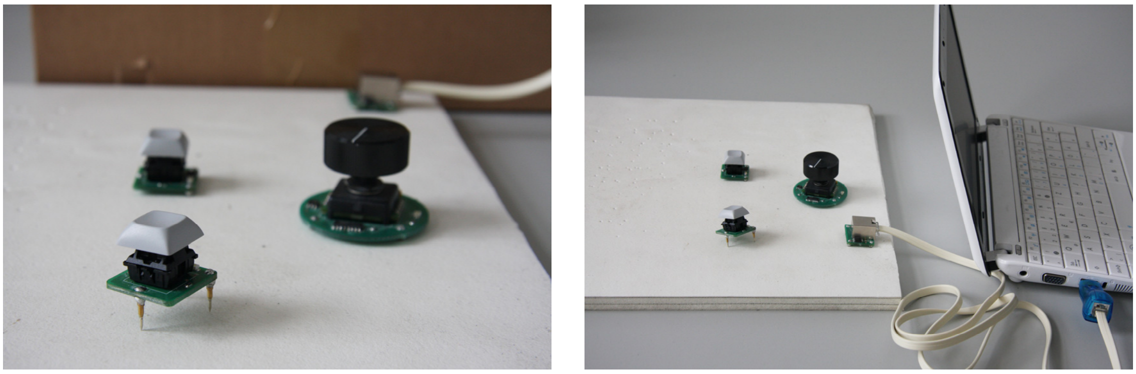


Figure 62. VoodooIO Toolkit. Left: Buttons and a knob placed on the substrate. Right: Connecting the substrate with the attached components to a netbook via USB.

In Figure 62, VoodooIO components on the substrate, which is connected to a netbook via USB, are shown. To summarize VoodooIOs main advantages, there is no restriction in placing the control units on the surface and the control units can be rearranged while the system is running. This allows different layout opportunities to be quickly tried out without having to restart an application.

6.1.2 Developing Support for Automotive User Interfaces

A lot of methods and tools are available for evaluating the effect of tertiary tasks on driving performance and distraction. A comprehensive overview of well-established approaches is already given in chapter 2.6. In contrast, there are only a small number of developing support methods for creating prototypes of automotive user interfaces that can be found in the open literature. Car manufactures may have their own internal development systems to fulfill their specific requirements, and published research indicate that prototypes are often directly implemented and integrated into driving simulation environments without any particular tool support. In the remainder of this section, a method for supporting early steps of the human-centred design process and two tool supports for rapid prototyping are presented. One of these tools already includes an evaluation method for predicting user performance time.

Support for Understanding the Context of Use and Specifying User Requirements

Wilfinger and colleagues [Wilfinger et al. 2010] use cultural technologies to provide an approach for researching backseat activities for a better understanding of the context of use. They packed a probing package with a roadbook, pens, markers, glue, sticky notes, a disposable camera, etc. and handed it to participants to record their experiences while riding in the backseat and brainstorm ideas for new technologies that would be useful for the backseat area. Someone can imagine using this method not only for researching backseat activities but also for understanding the context of use in a car and specifying user requirements as well.

Rapid Prototyping

Two different rapid prototype approaches for developing automotive user interfaces with different objectives will be described next. The first aims to extend virtual prototypes with physical devices to provide users with their first haptic experience and to take device placements into account. The second focuses on creating virtual prototypes for evaluating user interface ideas with user models for speeding up the evaluation process.

Bullinger and Dangelmaier [Bullinger, Dangelmaier 2003] of Fraunhofer IAO combined the virtual prototype approach with physical devices. Virtual prototypes of design ideas are created either by programming them directly or by using specific programs that don't require the design to have any programming skills. Mostly, interaction with the virtual prototypes is demonstrated by using a mouse or other pointing devices. This approach might be well-suited for user studies in the desktop domain, but it does not really fit the automotive user interface context, where the arrangement of manual controls plays an important role. Therefore, Bullinger and Dangelmaier developed a toolkit called Virtual Prototype and Testing system (VP&T), which consists of a set of reusable physical buttons, switches, rotary knobs and programmable turn-push buttons that are connected through a standardized protocol to a virtual prototype. This toolkit allows physical automotive user interface prototypes to be rapidly created. The prototypes can be either used in a real car or in a driving simulator. Unfortunately, no further information about the protocol and the implementation of VP&T could be found, which implies that the toolkit is not available for public use.

The second approach presented here is Distract-R from Salvucci [Salvucci 2009]. Distract-R relies on a cognitive model of driver behavior and predicts driver performance and distraction. This tool allows the designer to quickly and easily translate automotive user interface ideas into running prototypes and then evaluate the prototypes without having to run time-consuming driving simulators studies. The cognitive models for generating predictions of driver performance are encapsulated in Distract-R's internal engine so that the user does not need to have any knowledge of cognitive modeling.

The user only has to deal with the following five components [Salvucci 2009]:

- Rapid Prototyping: drag-and-drop interface for quickly creating new virtual interfaces with buttons, microphones, speakers, dials and displays.
- Modeling by Demonstration: user demonstrates the task behavior on the prototyped interface.
- Individual Variability: specific characteristics like driver age, steering style and desired stability can be specified by the user to adjust the study to specific target groups.
- Simulation Environments: selection of the driving environment in which the model driver performs his driving as well as his secondary in-vehicle task.
- Simulation and Visualization: results are calculated 1000 times faster than real-time and include task time, lateral deviation and lateral velocity.

Salvucci reported on three studies he performed with his colleagues to demonstrate the usefulness of Distract-R. He emphasized that designers with no cognitive modeling background needed less than 20 minutes to complete the entire design cycle of prototyping and evaluating. Furthermore, he stated that Distract-R is a tool for quickly reducing the space of different automotive user interface possibilities to the two or three options that are the least distracting and thus worth investigating further. He concluded with the statement: "At this time, Distract-R does not provide the final word of these best interfaces; human experimentation would still likely be needed for a more accurate assessment of their distraction potential." [Salvucci 2009]

6.2 Using the Design Space for Developing Novel Automotive User Interfaces

In chapter 3, we presented the design space for driver-based automotive user interfaces. One of its main purposes is to provide a graphical representation that offers a general basis for discussing existing and novel automotive user interfaces. The design space can be employed for exploring the context of use by creating graphical representation of existing cockpit layouts to compare them in terms of interaction opportunities for performing a specific task. For example, if radio interaction is in the focus of research, the design space offers valuable clues about where the input devices, e.g. knobs, buttons and microphones, could be installed in the car and which body part would interact with the system. Similarities and differences between different car models can also be easily detected.

For producing design solutions, the design space might help in early design stages to discover new possibilities and provides means for communicating and discussing them. Furthermore, it might also serve as a tool for documenting the design phases. Changes in new user interfaces can occur throughout the design process and with the design space, these changes can be tracked in a simple graphical representation for different prototype versions.

All of our user interface approaches introduced in case studies 1-5 are represented in the design space. By placing the required input and output devices into the 2-dimensional grid, it is easy to see where each device is installed in the car, which body part interacts with the input device, which human sense is targeted by the output and how input and output are connected.

In Figure 63, the graphical representation of a concept car that contains all of our proposed user interfaces is illustrated. It is an automatic transmission car with only the necessary devices for the driving task: a steering wheel and two pedals for the primary task, as well as windshield wipers and a turn indicator for the secondary tasks. All devices that we added to the cockpit are used for tertiary tasks. The car has two touchscreens, one mounted in the vertical center stack (for case study 3: *Gazemarks,* case study 4: gaze-based interaction, case study 5: driver-passenger video link and case study 2: handwriting text input) and the other on the steering wheel (for case study 2: handwriting text input). Two eye trackers track the driver's gaze on the touchscreen in the center stack area (for case study 3 *Gazemarks*, for case study 4: gaze-based interaction) and the HUD area (for case study 5: driver-passenger video link). A webcam captures the driver's face (for case study 5: driver-passenger video link). The microphone, loudspeakers and buttons on the steering wheel are needed for case study 4: gaze-based interaction. The steering wheel has six vibration motors integrated, three on each side (for case study 1: vibro-tactile output). While using the design space in the different projects, the introduction of new symbols was necessary. In case study 3, 4 and 5, the eye tracker was used as an input device, and we introduced a diamond shape to represent it in the design space. For the required camera used in case study 5, a lying cylinder was added. The extended legend for the design space can be found in Figure 64.

While examining the design space of existing user interfaces, it became evident that the right hand is the main interaction initiator in left-hand drive vehicles (see chapter 3). Looking at the graphical design space of "our concept car" with the new user interface ideas, there is an observable shift to input devices that are not operated by the driver's hand. The eye tracker, microphone and webcams all provide less obtrusive interaction opportunities.

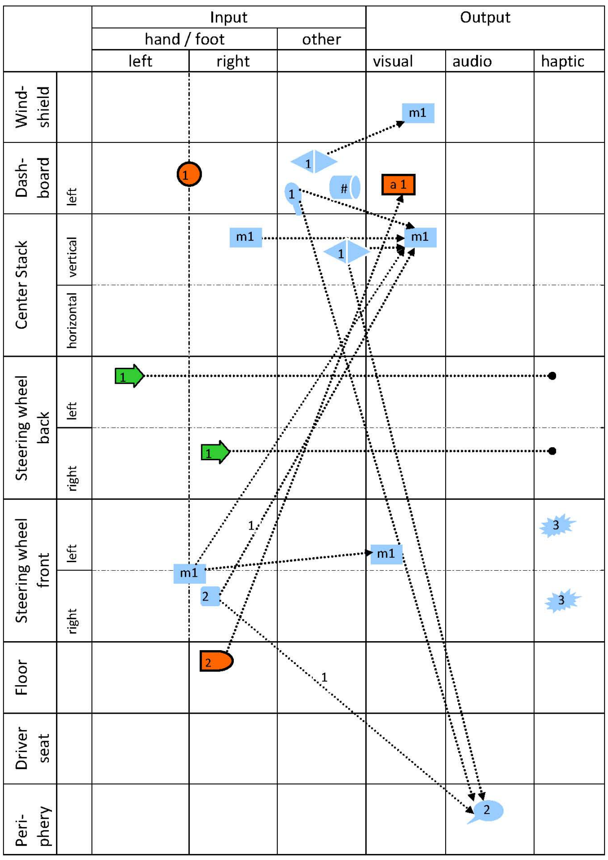


Figure 63. Graphical representation of a design space of a car including all user interface approaches presented in this dissertation.

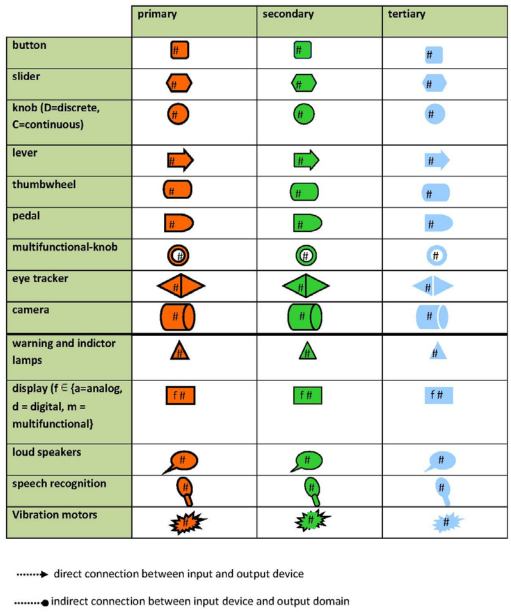


Figure 64. Legend for the design space of driver-based automotive user interfaces including the two new symbols for eye tracker and camera.

While exploring the design space for automatic transmission cars, a new input mechanism occurred to us. The space on the floor where the clutch pedal would have been mounted if the car had manual transmission could offer opportunities for using the left foot to provide input to an infotainment and entertainment system. In a Bachelor thesis [Pararasasegaran 2008] supervised by the author, we explored foot interaction as an additional modality in the car. Because the EIToolkit was used for developing two foot interaction prototypes, more details about this project will be presented in section 6.4.1.

6.3 Software Support for Modeling Interaction with Automotive User Interfaces

As described in chapter 2.6.8, the Keystroke Level Model (KLM) is seen as a reliable and valid means for modeling human performance that does not require working prototypes and user studies. Oftentimes, only a paper prototype or design sketch is needed for calculating total task time. Depending on the length and complexity of the task sequence being researched, the approach of using "paper and pencil" for calculating the predictive task time might be time-consuming and error-prone. Therefore, there are some research projects that support designers in generating predictive cognitive models of user behavior by demonstrating the task in a virtual mock-up of a user interface, e.g. [John et al. 2004; Holleis, Schmidt 2008]. These tools are, however, designed to predict task completion times with a more or less fixed layout of input devices, e.g. in a desktop setting or on a mobile phone.

We developed a modeling tool especially for the automotive domain that takes different arrangements of input devices, as well as their mappings to the tasks they support, into consideration. For example, the radio volume could be adjusted by turning a knob or by pressing a button a few times. Our tool, called MI-AUI (**M**odeling **i**nteraction with **a**utomotive **u**ser **i**nterfaces), aims to support the transition from a simple design sketch drawn on paper or with a design tool to a virtual "clickable" prototype. With MI-AUI, task completion times can be predicted using an integrated KLM. Furthermore, MI-AUI provides a means for connecting the virtual prototype to the tangible toolkit VoodooIO (see [Villar, Gellersen 2007] and chapter 6.1.1) for combining task time predictions with real interaction times.

6.3.1 Generating the Clickable and Tangible Prototype

The first step is to create a sketch of a new automotive user interface idea or to take a picture of an already existing user interface therewith an application should be controlled. The sketch or picture has to be loaded as a background image to MI-AUI (see Figure 65a). In a next step the input elements have to be tagged by clicking at two opposite corners of the element and it has to be specified which kind of input device it represented, e.g. a knob, a rectangle button or a round button. A colored marker on the element indicates its representation (see Figure 65b). Round buttons are red, rectangle buttons are yellow and knobs are blue.

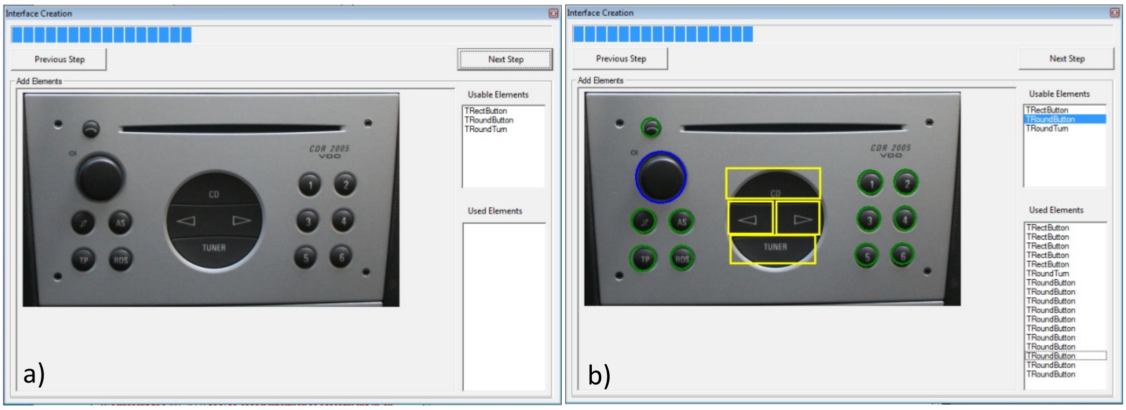


Figure 65. Creating a virtual prototype with MI-AUI. a) load an image or design sketch, b) mark buttons and knobs.

For linking VoodooIO elements with input devices presented in the sketch the desired VoodooIO element has to been selected from a list and afterwards the user has to click on the input device that should be connected to the VoodooIO element. After creating the prototype it has to be saved and an image can be printed for arranging VoodooIO devices at the right places in the design sketch (see Figure 66).

Figure 66. Creating a tangible prototype using VoodooIO [Villar, Gellersen 2007]. The left photographs shows control units being placed on a picture that shows the layout of a radio. On the right side, the completed tangible prototype is shown connected to a netbook.

6.3.2 KLM Operators and Task Times

The selection of key stroke level operators provided in MI-AUI is based on findings in [Green 1999a; Pettitt et al. 2006b; Holleis et al. 2007; Pettitt et al. 2007]. Additionally, we added the turn operator for interacting with rotatable knobs. The assigned times for each operator were measured in a user study. We asked 13 participants (6 female and 7 male, aged 17 to 28 with an average of 22.38) to perform four different tasks with a commercial radio system using buttons and knobs. The tasks were activities such as switch to tuner mode, switch to preset radio station one, increase volume by turning knob 90 degrees, switch to preset radio station four and decrease volume by turning knob 180 degrees. The list of operators for an automotive KLM is then determined by analyzing the video footage taking during the study. These operators and their assigned times are shown in Table 11.

A validation study then compared actual total task times of ten participants (3 female, 7 male, aged 23-55 with an average of 22.38) to predicted task times using the operators listed in Table 11. The participants performed eight different tasks. The study's results showed that seven out of eight task prediction times were in the suggested range of 20-30% Root-Mean-Square error [Card et al. 1980].

Operator	Description	Time (sec)
H	Homing Wheel – System Homing System – Wheel	0.893 0.811
K	K (pressed button once) K (pressed button twice) K (pressed button X-times)	0.536 1.760 2.124+0.221*(X-3)
T	Turn 45° clockwise Turn 90° clockwise Turn 180° clockwise Turn 45° counterclockwise Turn 90° counterclockwise Turn 180° counterclockwise	1.095 1.161 1.742 0.8 1.1142 1.4
F	Move finger between controls	1.143
R	Response time depending on system	X
AS	Predictable list	0.303
M	After R operator After T operator	1.35 1.179

Table 11. Overview of automotive KLM operators used in MI-AUI.

More importantly, the average performed task times of these 7 tasks were lower than the predicted times. Hence, the user interface does not distract the driver more than our automotive KLM predicts. Detailed information about finding the desired operators and on the user studies can be found in [Schneegaß 2008].

6.3.3 Predicting Task Completion Time

For predicting task completion time, MI-AUI provides two different modes: click mode and VoodooIO mode. In click mode, performing a task is demonstrated by clicking on the input devices specified while creating the virtual prototype. For example, the user selects radio station one by clicking on the assigned button and increases the volume by clicking on the knob and in the window that appears, where he can click to specify how many degrees the knob should be turned.

MI-AUI calculates the predicted task time in two ways and provides a graphical representation of the assigned KLMs. The first calculation of the KLM is done with the assumption that the task is performed in a stationary situation. In the second calculation, the adaption of the occlusion technique to the KLM calculation as proposed by Pettitt et al. [Pettitt et al. 2007] is utilized. A detailed description of the occlusion technique can be found in chapter 2.6.5.

For including this technique in MI-AUI, we defined a vision and an occluded period of 1.5 second and formed four assumptions (derived from Pettitt et al. [Pettitt et al. 2007]) that had to be considered while placing the operator.

4. During vision periods, every operator can be placed as in the original KLM.
5. Operators that are not related to vision can be placed as in the original KLM.
6. If an operator needs vision, it can only be placed when the remaining vision period is long enough; otherwise, it has to be placed directly after the next occluded period.
7. Operators that do not need full vision after being initiated can continue to be performed in occluded periods, e.g. turning a knob.

These rules were applied to the stationary KLM and led to shifts in the KLM predictions and consequently longer task times.

In Figure 67, the KLM for a stationary situation is shown on the left side and an estimation based on the occlusion technique is presented on the right side.

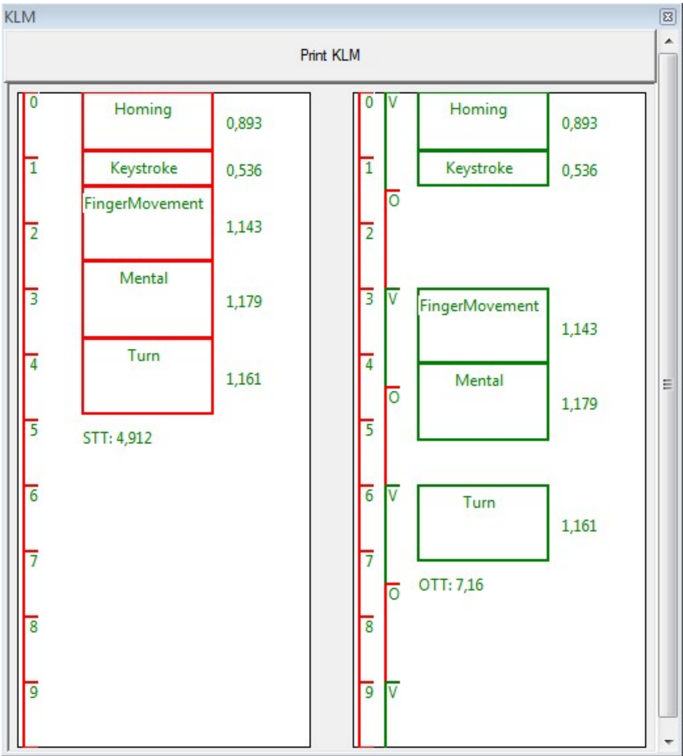


Figure 67. Graphical representation of a calculated Automotive KLM by MI-AUI. On the left side, a stationary situation is shown, and on the right side, the KLM has been enhanced by the occlusion protocol.

To use the VoodooIO mode, an image of the virtual prototype has to be printed out so that VoodooIO devices can be arrange on it according to their placement in the design sketch (see Figure 66). The idea is to provide a first user experience and to combine KLM times with real performance times while using the new interface. For example, this makes sense especially when using the knob. With our user study results, it was not possible to find a function to estimate all degrees for the knob. Therefore, we decided to provide values only for 45°, 90° and 180°. While using the VoodooIO knob, the turn value can be more flexibly measured. As a result, the corresponding KLM can be calculated and graphically represented like it is in the click mode (see Figure 67).

6.3.4 Implementation

MI-AUI is implemented in Free Pascal using the Lazarus IDE. For predicting total task time, we utilized the *KLMstub* that Holleis et al. [Holleis 2009; Holleis, Schmidt 2008] implemented in the EIToolkit and adapted it to our automotive KLM requirements. The *KLMstub* automatically generates a Keystroke-Level model based on mappings from actions to time values specified in a XML document. The implemented KLM can easily be updated and extended without changing anything in MI-AUI. For connecting the VoodooIO toolkit to MI-AUI, we also used the EIToolkit and developed a *VoodooIOstub*. This stub provides VoodooIO data in the EIToolkit protocol and can therefore be used by any other application.

6.4 Utilized EIToolkit in the Prototype Developing Process of Automotive User Interfaces

In several of the presented projects the EIToolkit was used for creating prototypes for new automotive user interfaces. The EIToolkit was invented and implemented by Holleis et al. [Holleis 2009], and we expanded it with new stubs and applications that were required for our projects. Some of our additions are especially designed for the automotive context but others are also usable in other pervasive computing contexts. Before providing a list of new integrated stubs in the EIToolkit, one more concrete example with foot-computer interaction will be presented to further demonstrate how EIToolkit can be used to significantly speed up the development process.

6.4.1 Using EIToolkit for Exploring Foot-computer Interaction as an Additional Modality in Cars

As previously mentioned, while exploring the design space of automatic transmission cars, we came up with the idea of providing input to an infotainment or entertainment system by using the left foot. We developed an application that provides a list of music artist and on a lower level a list of music titles. This music application used a *ListStub*, which listens to instructions (like “next/previous item” and “select item”) for interacting with the list.

We developed prototypes for two different foot interactions (see Figure 68). In the first option, the driver can scroll through the list by moving his foot consistently from left to right and from right to left. He selects a music title by perform a “click” with the foot, i.e. lifts the foot up and down again. The second option enables continuous scrolling through the list. If the heel stands still and the ball of the foot moves to the right side and stays there for a while, the list scrolls incrementally downwards; and if the ball of the foot moves to the other side, the list scrolls upwards. To stop continuous scrolling, the driver has to move the ball of his foot back to the initial position. A music title is selected by the same “click” maneuver performed in the first option.

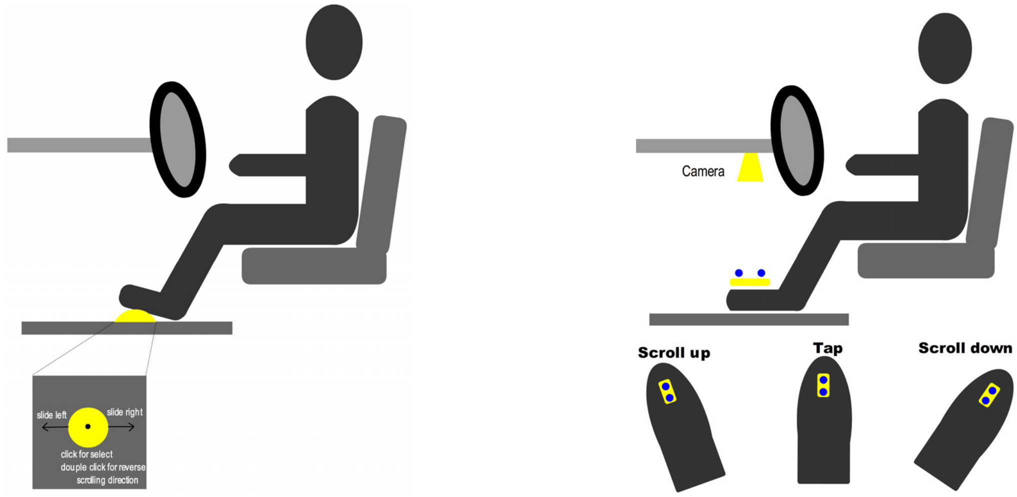


Figure 68. Two different foot interaction options. On the left side, interacting with a trackball is illustrated, and on the right side, using input gestures (captured through a webcam) for scrolling through a list is shown.

For the two prototypes, two completely different hardware devices were chosen. For the first option, we used a BIGtrack Trackball [@infogrid], which provides x- and y-coordinates. The second option was based on image processing with two infrared light-emitting diodes mounted on the foot and a webcam that records their relative position. We developed a stub for each input option (*TrackballStub* and *IRStub*) that transfers the input data from the trackball and the image processing setup to the Common Communication Area in the EIToolkit data format. An application called *ListInteraction* gets these data and generates the commands "up", "down", "click", which are executable by the music application. Later on, while preparing a user study, we wanted to compare foot interaction with hand interaction. We developed a button interface that is operated by the driver's right hand and consists of three buttons: one for scrolling down, one for scrolling up and one for selecting an item. To realize this interface, only a single new stub and a few lines of code in the *ListInteraction* application had to be added. The music application remained untouched. During the user study, the music application could be kept running the entire time. Only the different stubs had to be started in the different conditions. An illustration of the prototypes with the four different subs and the two applications is shown in Figure 69.

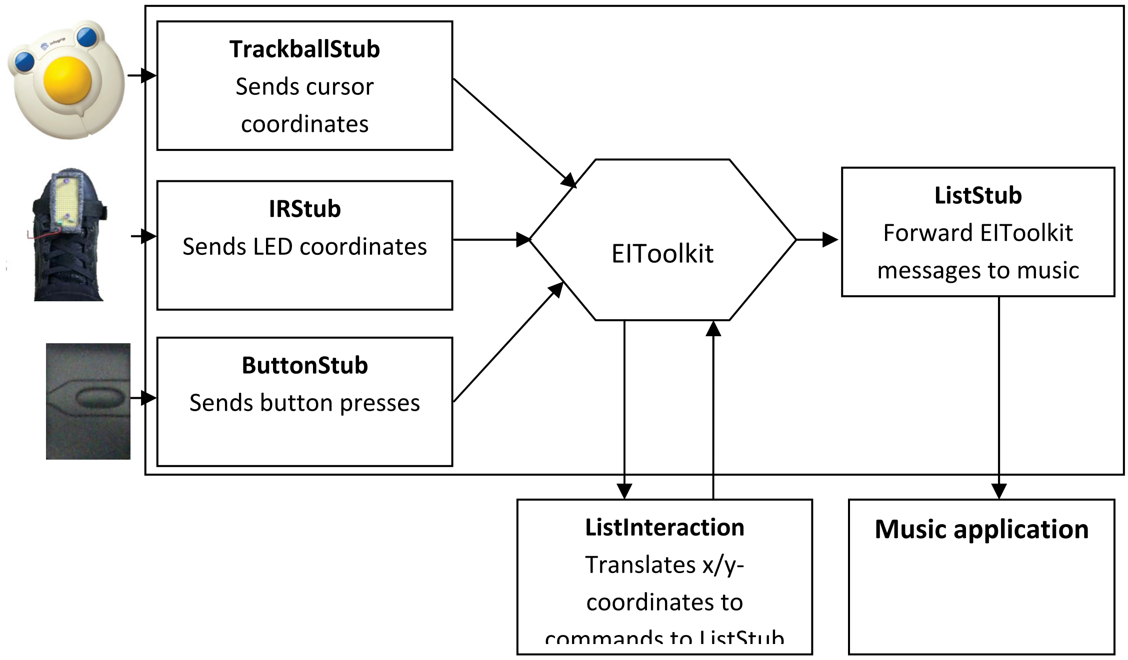


Figure 69. Illustration of the prototypes for foot-computer interaction using the EIToolkit. Adapted diagram taken from [Holleis 2009].

For the sake of completeness, we will briefly report on the results of a conducted user study. 12 participants executed selection tasks with the music application, e.g. “Please select Alicia Keys’ song Falling”, while performing the LCT (chapter 2.6.4, [Mattes 2003]). We compared three different conditions: 1) operating the button interface with the hand, 2) operating the trackball interface with the left foot, and 3) operating the gesture interface also with the left foot. The results show no significant difference in driving performance, although participants performed best while operating with the hand. Answers given by the participants in a questionnaire indicate that they preferred the hand interaction. Most users are familiar with and well-trained in hand-computer interaction. We believe that with more practice foot interaction might also become more natural. Long-term studies are needed to prove this conjecture.

6.4.2 New Stubs and Applications Integrated in the EIToolkit

In Table 12 new stubs and applications in the EIToolkit are listed that were developed in context of this dissertation. For each component a short description is given. More information about the stubs and applications and their usage can be found in the referenced project representations and published papers.

Name of component	Type	Description	Used in …
EyetrackerStub	stub	Listens to eye tracker messages provided by Tobii SDK and forwards them in normalized coordinates to the EIToolkit	Case study 3 (chapter 5.3 and [Kern et al. 2010b]) Case study 4 (chapter 5.4 and [Kern et al. 2010a] Case study 5 (chapter 5.5 and [Tai et al. 2009])
SteeringWheel Stub	stub	Forward EIToolkit messages as steering information to CARS	CARS (chapter 6.5)
TrackballStub	stub	Forward trackball cursor coordinates to EIToolkit	Foot interaction (chapter 6.4.1)
IRStub	stub	forwards IR light ID and its position to the EIToolkit	Foot interaction (chapter 6.4.1)
VoodooIOStub	stub	Listens to VoodooIO messages on specific telnet port and forwards them to the EIToolkit	MI-AUI (chapter 6.3)
KLMStub	stub	Already existing stub in EIToolkit adapted by automotive KLM values	MI-AUI (chapter 6.3)
WiiSteering App	application	calculates steering information from WiiRemote motion sensing data and forward them to the EIToolkit	[Döring et al. 2011]
ListInteraction	application	transforms x/y coordinates into list information (“next”, “previous”, “select”) and forward them to the EIToolkit	Foot interaction (chapter 6.4.1)
ListStub	stub	listens to list messages and used them to control a list application	Foot interaction (chapter 6.4.1)

Table 12. List of new stubs and applications added to the EIToolkit.

6.5 Measuring Driving Performance with CARS – Configurable Automotive Research Simulator

A few case studies’ descriptions already contain references to CARS [Kern, Schneegaß 2009], because the “Configurable Automotive Research Simulator” (CARS) was utilized for evaluation purposes in their studies. At this point, CARS should finally be introduced in more detail.

When we first started doing research in the field of automotive user interfaces, we were confronted with the problem that there are no open source driving simulators available for flexible automotive user interface evaluation. To fill this gap, we started developing

CARS, our own driving simulator software as an open source project (available at http://cars.pcuie.uni-due.de/).

CARS is the result of a project seminar (winter term 2007/2008) and a bachelor thesis [Müller 2008] supervised by the author and is still an ongoing project. In the following section, we present the requirements for the development of CARS. Detailed descriptions of CARS's components, the map editor, simulator and analysis tool, are also given. A few implementation details will follow, and finally, results from an initial user study are presented to demonstrate the usefulness of CARS for measuring driver distraction.

6.5.1 Requirements Analysis

The following list shows the most important requirements and features upon which CARS was built:

Open source software: CARS shall not only be freely accessible for other researchers, it should also be open source and easy to adapt to different user study requirements.

Low cost: A standard simulation shall run on a consumer PC, equipped with at least one visual output (display or projector) and a game steering wheel with gas and brake pedals for maneuvering a virtual car. For test purposes, controlling the car with the keyboard shall also be possible.

3D driving environment: A virtual car shall be maneuvered by a user through a 3D-driving environment. A first person view perspective shall be shown so that the user sees the 3D world as he would see the real world while driving a car.

Classical street view scenario: A "simple" street view scenario shall be presented to the driver. Street elements, like straight forward roads, curves, crossroads and t-crossroads, shall be included in a basic set of the simulator.

Add new environment elements: CARS shall provide interfaces with which new elements, like multilane streets, traffic lights, traffic signs or elements for decorating the environment (e.g. trees or houses) could be easily added.

Support for creating the virtual driving environments: Tool support for creating the virtual world shall be provided to the experimenter. A virtual world shall be created through a few mouse clicks in a few minutes.

Automatic analyses of driving performance: Standard measurements that indicate driver distraction, like mean distance to a racing line or lateral speed, shall be calculated automatically after finishing the test trials.

Connection to additional devices: CARS shall support connection to additional devices, like navigation systems or external speedometers.

Supporting different input devices: Steering input shall be independent of the concrete input devices. Interacting with CARS shall be possible with a steering wheel, as well as with other input devices.

Supporting early stages in the design process: CARS shall be designed to support the early stages of a development process for automotive user interfaces by providing a concrete basis for making design decisions. So far, CARS shall not provide an absolute proven measure of real driver distraction; it shall rather provide the developer with indicators of driver distraction.

6.5.2 Concept of CARS

We developed a concept for CARS that includes a 3D virtual driving environment. The visual output shows a first person view on a forward roadway. The virtual world is specified by coordinates (x, y, z). To be able to provide an abstract view of the virtual world, we divided the xz-layer into a grid consisting of map fields with a corresponding real-world size of 8.3m x 8.3m. We chose 8.3 m for the height and width of a map field, because the usual street width (with two lanes) is about this size. In the current version of CARS, only flat courses without any hills are considered; therefore, the y-coordinate is set to a constant value.

Virtual driving environment

CARS basic driving environment consists of straight forward streets (from west to east, from north to south and vice versa), curves (in all four directions), crossroads and t-crossroads. These elements enable simple driving settings to be created and arranged in a loop, so that "endless" tracks can be utilized in a user study. A set of traffic signs (e.g. speed limit 30, speed limit 50, yield) allow traffic on the road to be controlled. Traffic lights can be controlled by trigger fields, which means when the car drives over an "invisible" trigger, the traffic light at the next crossroad will turn red. These trigger fields enable the same driving setting, independent of the speed of the car or other conditions, to be created. They can also be used to start a ball rolling across the street or to start another car that crosses the main car's path. Currently, additional cars are restricted to driving along straight forward roads at a constant speed. Also, objects like houses and trees are available in the basic version of CARS for decorating the driving environment.

CARS consists of three main components that are connected through log files with each others, so that each component can run separately and can be substituted, as long as the format of the log files stays the same. A graphical representation of the components is illustrated in Figure 70.

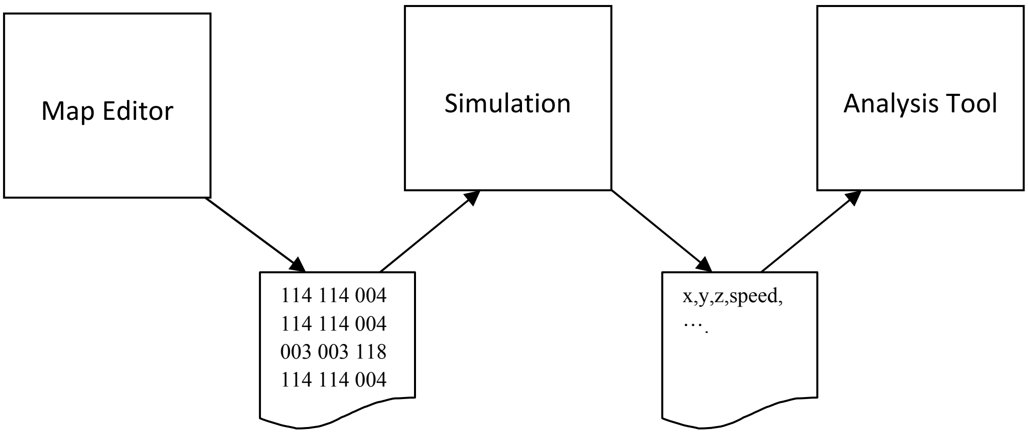


Figure 70. Component diagram of CARS. The three components Map editor, Simulation and Analysis tool are loosely connected through log files.

Map Editor

A graphical map editor enables experiment designers to create the virtual driving environment. In Figure 71, the graphical user interface of CARS's Map Editor is shown. At the beginning, the number of map fields in the driving environment must be specified. The created map has a grid layout and is initially covered with grassland. Street elements presented on the left side can be selected and placed in the driving environment by clicking on the desired map field. The map field then changes into the desired street element. While placing straight forward roads on the map, the Map Editor provides a means for speeding up the creation process. After selecting a map field for placing a straight forward road, red markers are shown on the map and allow the end position of a road to be marked (see Figure 71). All map fields between the start and end points are then filled with straight forward roads. Furthermore, the map designer can specify the starting position of the car by placing the starting-point map field on any straight forward map field. After saving the map, an output file is generated with corresponding numbers for each map field, e.g. 014 stands for grassland and 003 for a horizontal straight forward road (see Figure 72).

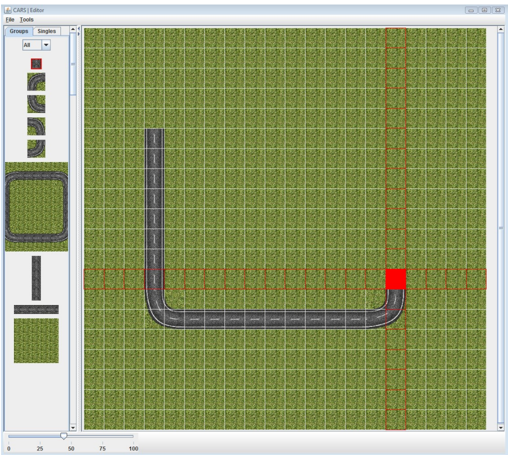


Figure 71. Graphical user interface of CARS' Map Editor.

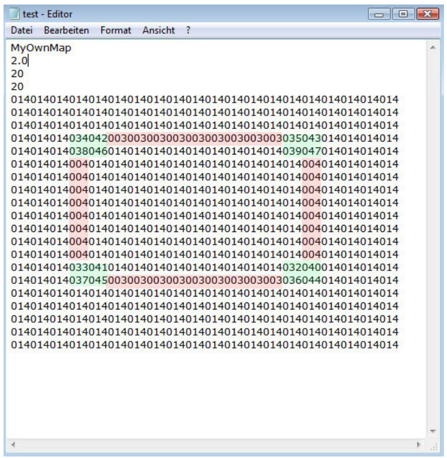


Figure 72. Output file of CARS' Map Editor. Each triple stands for one street element. The created track is highlighted in red (for straight forward roads and green for curves).

Simulation

To create the virtual driving environment, the simulation tool first reads Map Editor's output file. According to this information, the simulation tool renders a view of the world from a driver's perspective (see Figure 73). The user can drive the virtual car by using the steering wheel controller, the keyboard or other input devices. The current speed is shown on the bottom of the simulation screen or on a separate speedometer display.

Figure 73. Driver's view of the 3D driving environment

While driving, the following data are stored in an output file at a rate of 20Hz for later analysis of the driving performance:

> x-position, y-position, z-position, speed, time, steering wheel position, pedal position, breaking activity, racing line distance

Analysis Tool

CARS's Analysis Tool delivers detailed information about driver performance and calculates parameters that describe the level of driver distraction. The analysis tool reads Simulation's output file and calculates statistics mainly based on measurements performed in [Green et al. 1994; Reed, Green 1999]:

Mean distance to the racing line is calculated based on the car's position on the street and an ideal racing line (see Figure 74). Each straight forward street map field has an ideal racing line given by the straight line defined by two points: $p_1=(x_1, y_1)$ and $p_2=(x_2, y_2)$. Ideal racing lines on map fields showing curving streets are approximated by a number of points that are connected through straight lines. The car's position on the map is given by (x_f,y_f)- coordinates of the center point of the car on the map. The distance to the ideal racing line is calculated by:

$$d = \frac{ax_f + by_f + c}{\sqrt{a^2 + b^2}} \qquad (1)$$

where a, b and c are calculated by

$a = x_1 - x_2$

$b = y_1 - y_2$

$c = -(ax_1 + by_1)$

The mean distance to the racing line is given by:

$$mrl = \frac{\sum_{i=1}^{n} |di|}{n} \qquad (2)$$

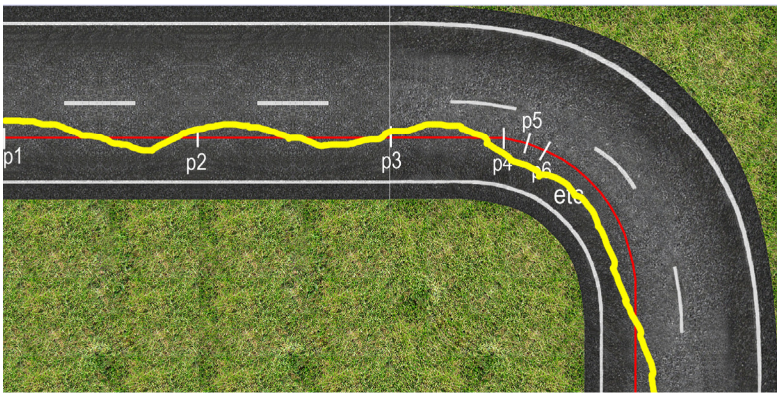


Figure 74. CARS's ideal racing line (red) is given through points p1, p2, etc. The yellow line shows a performed driving course.

Standard deviation of the mean distance to the racing line is calculated with the following mathematical formula:

$$sdrl = \sqrt{\frac{1}{n-1} * \sum_{j=1}^{n}\left(x_j - mrl\right)^2} \qquad (3)$$

where mrl is the mean distance to the racing line calculated by formula (2). A high standard deviation of the mean distance to the racing line indicates an unsafe driving behavior, because the vehicle does not stay constant in the line.

Mean lateral speed can also estimate if the driver is able to keep the lane constantly or if he needs corrections to achieve this goal. If the car is constantly parallel to the ideal racing line, the mean lateral speed is zero, but the more the driver steers the car across the lane, the higher the mean lateral speed is. Lateral speed is calculated by the difference of two consecutive distances to the ideal racing line divided by their time lag.

$$ls = \frac{d_2 - d_1}{t_2 - t_1} \qquad (4)$$

where d_1 and d_2 are calculated by formula (1), and t_1 and t_2 are the points in time when the respective distances were measured.

Mean lateral speed is calculated by:

$$mls = \frac{\sum_{i=1}^{n} |ls_i|}{n} \qquad (5)$$

Mean speed is calculated from all collected speed values:

$$ms = \frac{\sum_{i=0}^{n} s_i}{n} \qquad (6)$$

Where s is the speed value at a given point.

Standard deviation of mean speed is calculated similarly to the mean standard deviation from the ideal racing line.

$$sdMS = \sqrt{\frac{1}{n-1} * \sum_{j=1}^{n}\left(x_j - ms\right)^2} \qquad (7)$$

where ms is the mean speed value measured during one drive, as calculated by formula (6).

Standard deviation of the steering wheel angle is calculated by:

$$sdSA = \sqrt{\frac{1}{n-1} * \sum_{j=1}^{n}\left(x_j - sa\right)^2} \qquad (8)$$

where sa is the mean steering wheel angle measured during one drive. On straight roads, a high mean deviation of the steering wheel angle shows that the driver needed little steering wheel activity to keep the car constantly on the track.

Standard deviation of throttle position is calculated similarly to the standard deviation of the steering wheel angle:

$$sdTP = \sqrt{\frac{1}{n-1} * \sum_{j=1}^{n}\left(x_j - tp\right)^2} \qquad (9)$$

where tp is the mean throttle position of one track.

Steering reversal frequency is the number of steering reversals over the time of one drive, where a steering reversal is a change in steering wheel position of more than 1 degree that takes longer than 0.33 sec.

$$srf = \frac{sr}{t_2 - t_1} \qquad (10)$$

where sr is the number of steering reversal, t_1=start time and t_2=end time of the drive.

Throttle reversal frequency is the number of throttle reversals in one drive, where a throttle reversal is a change in throttle position of 0.5% that takes longer than 0.33 sec.

$$trf = \frac{tr}{t_2 - t_1} \qquad (11)$$

where tr is the number of throttle reversals, t_1=start time and t_2=end time of the drive.

Off-road time is the amount of time during which the car is not on the street. This might be a helpful indicator to estimate the importance of the collected driving data. If a driver drove most of the time off-road, it would indicate that he had difficulties maneuvering the car in the virtual environment. Off-road time periods have to be longer than 100ms. Time periods less than 100ms are seen as making a slip.

Off-road frequency indicates how often the driver left the street in one drive.

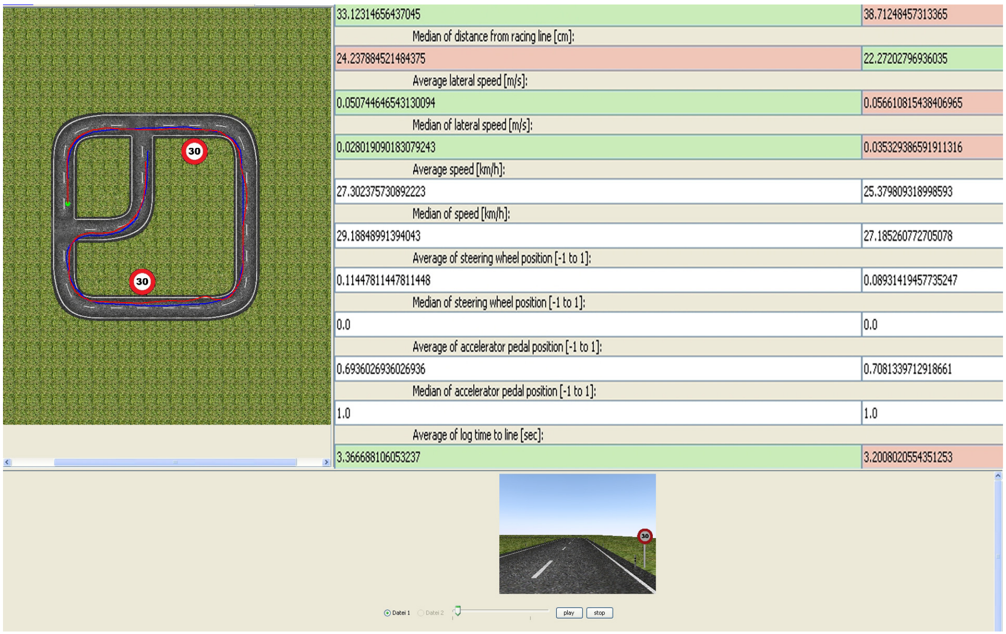


Figure 75. Graphical user interface of the Analysis Tool. Top left: Two drives (blue and red lines) under different conditions are represented on the track. Top right: Calculated driver distraction values. Button: Life view of one of the loaded file.

In Figure 75 the graphical user interface of the Analysis Tool is shown. It allows two log files to be loaded that include data for the same track but with different driving conditions for direct visual comparison (on the left side) and for comparison of calculated driving performance data (on the right side). The analysis tool provides the different calculations regarding driving performance and marks the better one with green and the worse one with red. Nevertheless, researchers must determine which of these data are most relevant for each test. At the bottom of the graphical user interface, the experimenter is able to start and stop a live view of one of the performed drives. The green dot on the track in the top left window indicates the driver's position in the trail. A slider enables the experimenter to navigate freely in the live view.

Implementation

CARS's three components are implemented in JAVA and thus compatible with all platforms that are able to run a Java Virtual Machine. Additionally, for rendering the virtual driving environment, OpenGL is required. CARS is an open source project and the source code, as well as online documentation, can be downloaded at https://svn.pcuie.uni-due.de/CARS/. In the following section, only a few key aspects of CARS's architecture and implementation shall be presented.

The driving simulation tool is based on the JMonkeyEngine (JME) [@jmonkeyengine], which uses the Lightweight Java Game Library [@LWJGL] (LWJGL) as an interface to OpenGL. In addition to JME, we use the JME physics engine [@Jmephysics]; this framework simulates physical interactions, e.g. gravity, in a world scene. In Figure 76, the system architecture is shown.

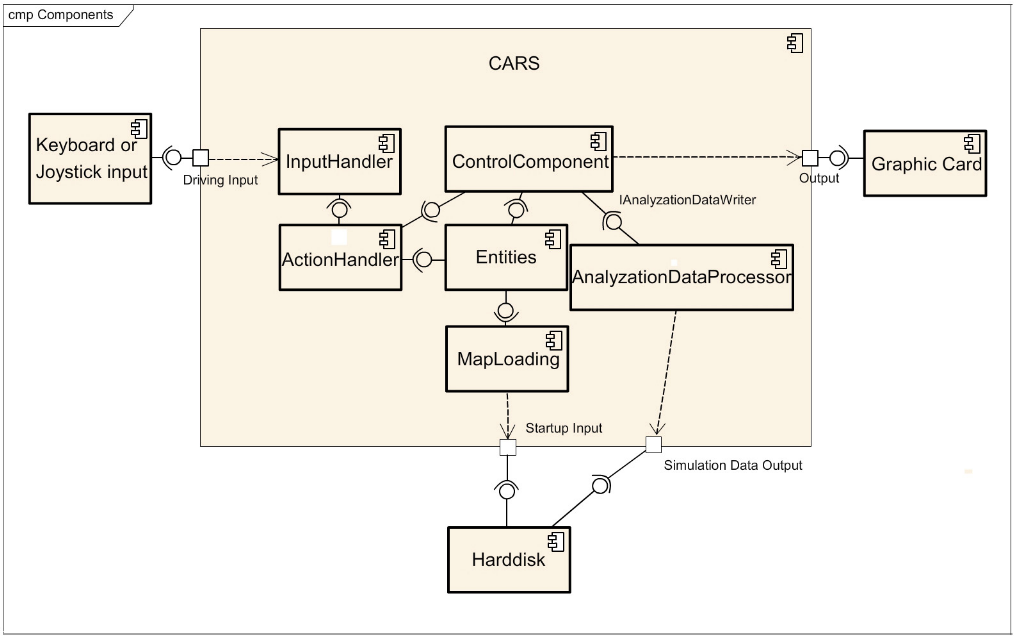


Figure 76. System architecture of CARS.

The main entities used in the simulator tool are the car, the map and any static objects that can be placed on the map, e.g. signs, trees, etc. An example from the jME Physics project provided the basis for our car with operations for steering, breaking, accelerating, etc. The car consists of two-wheel suspensions that can be moved separately in order to simulate a real life driving experience.

The virtual world that the car is driving in is represented by a map that consists of several MapFields. Each MapField contains information about its texture and its position in the virtual world. In the base layout, the main elements – straight forward roads, curves, crossroads and t-crossroads – are represented by MapFields. For creating a new element, a new texture has to be created which is used by a new instance of MapField. The new element has to be assigned to a unique number that correlates with its representation in the Map Editor. If the new element is a new street element, like a roundabout, the ideal racing line also must be added so that the Analysis Tool can calculate the driving performance for this new element.

For the steering wheel input, as well as for connections to output devices (e.g. speedometers), the EIToolkit offers a quick and easy way to add different devices to CARS. The steering wheel input is provided by a *SteeringWheelStub* that receives data from different input devices. So far, connections to different game steering wheels, as well as to the Wii controller, are available. A *SendStub* provides information about the current driving situation that can be used by output devices, like a display, to show the current speed or navigation information. With an update rate of 20Hz, driving information are stored in a text file that is used as an input file for the Analysis Tool.

The Analysis Tool is implemented with the model-view-controller concept. Each calculation described in section 6.5.2 is capsulated in single modules. This allows new calculations based on the provided driving data to be easily added. For presenting the live view, the stored driving data are used as input for a simulation that is started at the bottom of the Analysis Tool window.

6.5.3 Evaluation of CARS

We performed two initial evaluation studies (each with 10 participants) comparing tasks with different levels of difficulties, similar to the tasks that were used to evaluate LCT (see [Mattes, Hallén 2008]). In task T1, participants had to sort yellow sweets from a bag of colored sweets into a tray. In task T2, they had to identify and take specific coins out of a purse and then put them back into the purse again. In task T3, participants had to answer questions like "Which city is closer to city A: city B or C?" by referring to a paper road map of Germany placed on the front passenger's seat. The results show clearly that users tend to reduce the driving speed significantly when they perform a tertiary task, which compensates for their decreased ability to stay within the driving lane. Taken this into account, it was not surprising that we found no significant differences regarding lane keeping ability, e.g. in the standard deviation of the mean distance to the racing line. We suggest finding a factor for driver distraction that includes indications of lane-keeping abilities (e.g. lateral speed or standard deviation of the mean distance to the racing line) and mean speed. One opportunity might be to calculate the quotient of the standard deviation of the mean distance to the racing line and mean speed. We did this calculation for the results gained in our user studies and found significant differences between tasks that different greatly in their level of difficulty (between T1 and T3, as well as T2 and T3). There was no significant difference between T1 and T2. More experiments are needed to validate this value as a factor of driver distraction and to explore more opportunities for calculating such a factor. Ideally this factor would be sensitive to small differences in the effect that tertiary tasks have on driving performance.

6.5.4 Extending CARS Analysis with Eye Tracking Data and Physiological Data

Measuring driving performance in simulated driving environments often provides reliable and valid indications to decide if and in what way a given automotive user interface effects driver distraction. However, in cases where the user interfaces are very similar, it is not always possible to get significant results. We propose a combination of driving performance data with measurements of the visual demand that an automotive user interface has on the user. In current research, total eyes-off-road time is often used as a measure of visual demand while being engaged in a tertiary task [Young et al. 2003]. In the context of a Bachelor thesis [Hufen 2009] supervised by the author, CARS was extended by an analysis of glance behavior.

In a first step, a system was designed and developed that allows user's gaze on multiple displays and objects to be followed with one single eye tracker. This system is called MultiTracker, and in the automotive context, it can be used to record gaze in different areas of the driving environment, e.g. on multifunctional displays or static objects like a speedometer or a radio.

The MultiTracker system can be used within CARS's simulation tool and enhances driving data with the following gaze data:

POIID, POIType, gvPosX, gvPosY, lvPosX, lvPosY

POI stands for *point of interest*, which can be a display or an object. POIID identifies a unique POI, whereas POIType indicates if the POI is a display or a static object. All screens and objects are integrated in an overall coordinate system, and gvPos (global view position) specifies gaze coordinates in this overall coordinate system. On the other hand, lvPos (local view position) specifies gaze coordinates in the local coordinate system of a POI (see Figure 77).

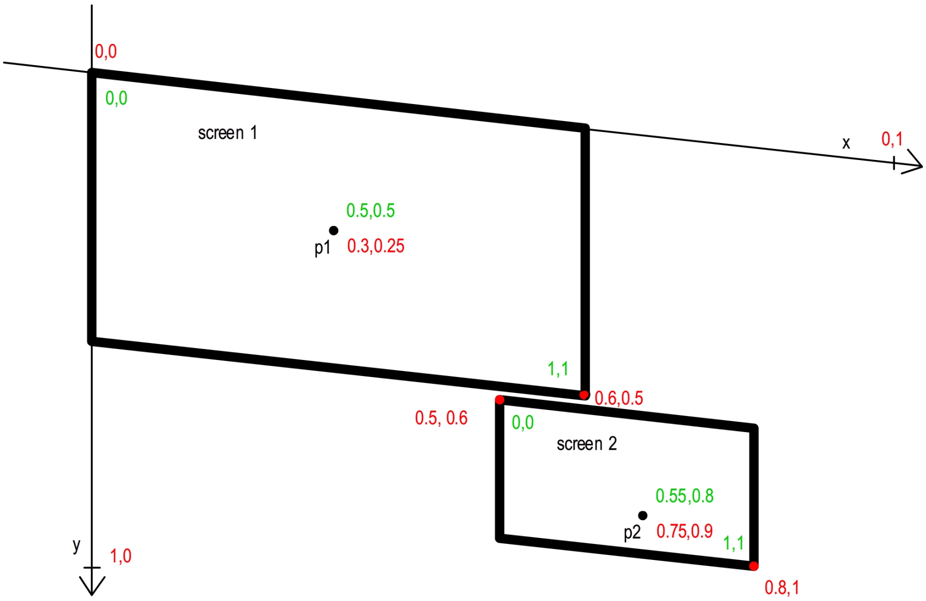


Figure 77. Schematically representation of a two-screen-setup that should be tracked with the MultiTracker. Global view positions (gvPos) are shown in red coordinates and local view position (lvPos) are shown with green coordinates. The two example points p1 and p2 have both global and local coordinates.

For calculating gaze behavior, the analysis tool is extended by the following functions:

- Frequency of eye glances on a POI
- Average eye glance duration on a POI
- Total eye glance duration on a POI

Glances shorter than 600ms are considered to be blinks and are therefore not included in the calculations.

The changes in the graphical user interface of the Analysis Tool can be seen in Figure 78. The graphical representation of the performed drive is extended by eye glance data. The different objects and screens are assigned to different colors, and the racing line is pigmented according to which object or screen the user looked at (see Figure 78). During playback of the live view, the current view point is indicated by a green point both directly in the live view image and in the schematic representation of the setup.

The graphical representation enables experimenters to draw conclusions about driving and eye glance behavior. For example, if a driver performed very badly over a period of time, the representation can be examined to see if looking away from the road scene might help explain the bad performance.

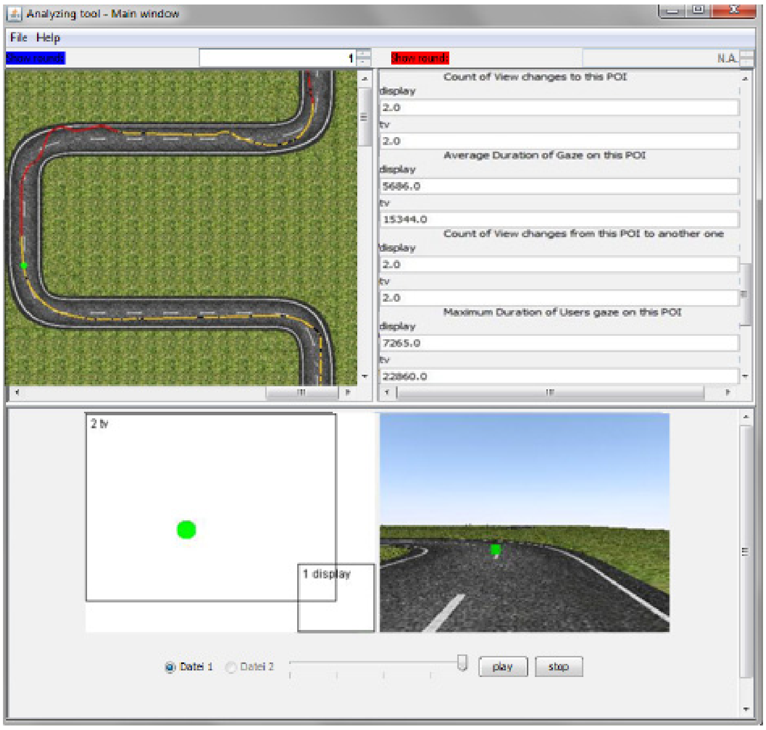


Figure 78. Graphical user interface of the analysis tool extended by eye tracking data. Top left: Racing line is color coded to indicate at which point and at which object or screen the driver looked at. Top right: Calculations of eye glance behavior. Bottom: live view with corresponding view point in the 3D driving environment and in the schematic representation of the setup.

We have already started to integrate physiological measurements in CARS. We used a NeXus-10 [@mindmedia] from Mind Media BV for collecting physiological data from the driver while he performed a tertiary task. NeXus-10 transmits data with an update rate of up to 2048 samples per second over 10 channels via Bluetooth. Measured data are, for example, EEG data (electro-encephalogram), ECG data (electro-cardiogram) and Galvanic skin response data. We developed a stub that transfers this data to EIToolkit's Common Communication Area. This stub allows for physiological data to be integrated in CARS so that the Analysis Tool might be used to discover which user interface generates more stress. In the next steps, adequate measurements to determine the level of stress from the raw physiological data must be identified, and then, a suitable graphical representation to link the data to the driving data must be created.

6.6 Discussion

In this chapter, we presented methods and tools that support a human-centred development process in the automotive user inter face domain. The design space for driver-based automotive user interfaces can help to understand and specify the context of use by offering a means for creating a benchmark of existing user interfaces. In the "Produce design solution" step, the design space should help to generate new interface ideas and to document them. We illustrated how the graphical representation of a design space would look for a concept car that includes all of the user interface ideas that we introduced in case studies 1-5.

With MI-AUI, we developed a rapid prototyping tool for predicting task completion times based on the key-stroke level model. Furthermore, a connection to the VoodooIO toolkit integrated in MI-AUI allowed us to quickly and easily create the first tangible user interfaces based on paper prototypes. These tangible user interfaces could be used to enhance the KLM calculation, as well as to let potential users experience how interaction with such an interface might be.

The EIToolkit helps us to create our prototypes in almost all of the presented case studies in this dissertation. Its usefulness for the development process of automotive user interfaces is illustrated in the foot interaction project as a concrete example. A list of stubs and applications summarized the components that were integrated in the EIToolkit in the context of our case studies. Some of the components are best suited for the automotive context, but others, e.g. the list interaction, could also be useful in other pervasive computing contexts.

Evaluating automotive user interfaces to determine their effects on driver distraction is a key issue in the development process. In a later stage of the design cycle, shortly before a new user interface becomes a real product, comprehensive driving simulator studies or field trials are the preferred and most reliable methods for assessing the usability of the user interfaces while driving. However, for deciding if a new user interface idea is suitable for the driving context and thereby worth the development effort and costs, tools for evaluating the idea early on are needed.

Similar to the LCT simulation, we used CARS in an early stage of the design process of automotive user interfaces. CARS provided us with a means for detecting if new interaction designs for tertiary tasks caused high driver distraction and should be discarded or adapted further. Contrary to LCT, CARS allows the driver to control the driving speed and the experimenter to create a driving environment that satisfies his needs. CARS is an open source project with three main components: a virtual environment creator, the actual driving simulation and a driving data analysis tool. The analysis tool calculates driving performance data, e.g. mean speed, mean distance to racing line and mean lateral speed. We extended the analysis function in CARS by integrating gaze behavior, which offers valuable clues to driver's visual demand and its effect on driving performance. Extensions for measuring driver's stress levels are planned.

CARS calculates a lot of different indicators for driver distraction based on driving performance data, eye tracking data and (in the future) physiological data. Each indicator can be used individually or in combination with one another to determine how distracting a researched automotive user interface might be, but this approach still leaves room for interpretation. We aim to find an opportunity to combine all collected and calculated values in a consistent and general way into one single factor that reflects the level of distraction an automotive user interface causes. It remains to be verified whether it is even possible to determine such a factor.

7 Summary and Future Work

In this dissertation, we presented our research results in the field of automotive user interfaces. Our work offers two main contributions to this field. First, we provide tools and methods for supporting a human-centred design process. Second, we designed and evaluated innovative interaction techniques and applications in the fields of multimodal, implicit and gaze-based interaction in the car.

7.1 Summary of the Contributions

7.1.1 Development Support

We took up the "Human-centred design for interactive systems" lifecycle [ISO 9241-210:2010] and focused on providing tools and methods that are especially suited for the automotive user interface domain and support the four key requirements: (1) Understand the context of use, (2) specify user requirements, (3) produce design solutions and (4) conduct evaluation. In this section, our tools and methods will be presented and discussed in the context of those four key issues.

Design space for driver-based automotive user interface

In chapter 3, we proposed a design space for driver-based automotive user interfaces as a methodical approach for analyzing, comparing and discussing automotive user interfaces. The design space is based on photographs we took of 117 different car models at IAA 2007 in Frankfurt. We provided a list of input and output devices that are commonplace in modern cars. In a two-dimensional graphical representation of the design space, corresponding symbols of these input and output devices can be placed according to the position where they are mounted in the car (e.g. dashboard, center stack, or steering wheel), the body part that interacts with the devices (mainly hand or foot) and the human sense (visual, audio, haptic) that is addressed by the output. With this graphical representation, the cockpit of a single car can be classified. An abstract view for classifying a set of cars is also introduced.

The design space, as well as its graphical representation, is extendable by inserting new columns for body parts and human senses that are not yet represented, by inserting new rows for alternative positions in the car and by adding new symbols for new input and output modalities. We used the design space in all of our case studies presented in this dissertation and even added new symbols, e.g. to represent an eye tracker as an input modality in the car.

The main aim of our design space for driver-based automotive user interfaces is to support interface designers in the following stages of the development process: 1) "Understand the context of use" by offering a means for analyzing and documenting existing cockpit layouts, 2) "Specify user requirements" by deriving and documenting user requirements regarding concrete input and output devices and their placements from the aforementioned analysis, 3) "Produce design solutions" by supporting designers in identifying new opportunities for interaction and placement of controls and output devices, allowing them to compare alternative user interface ideas, providing them with a common basis for discussion and helping them document their design decisions.

Rapid prototyping tool for modeling interaction with automotive user interfaces

With MI-AUI (Modeling Interaction with automotive user interfaces), presented in section 6.3, we provide a tool that supports the two design processes "Produce design solutions" and "Evaluate". MI-AUI offers a means for rapid prototyping based on a design sketch or a photograph of a car cockpit. With a few clicks, a virtual prototype can be created and the integrated keystroke level model can predict a driver's task time in a few seconds without the need for time-consuming and costly user studies. The utilized KLM operators and their assigned task times were measured and verified in user experiments. Furthermore, with MI-AUI, the first tangible prototypes of design ideas could be created using the VoodooIO toolkit [Villar, Gellersen 2007].

Use and extension of EIToolkit for speeding up the development process of automotive user interfaces prototypes

We used and extended the EIToolkit [Holleis 2009] for case studies 3, 4 and 5, as well as for the development of MI-AUI, the CARS driving simulator and other projects. This toolkit contributes to the design cycle stage "Produce Design solutions". Due to its stub concept, our development process could be expedited. To give only one example, we were able to develop a stub for getting eye tracking data from the eye tracker and used this data in different applications programmed in different programming languages. The stub itself was written without having to consider which eye tracker actually delivers the data and what the raw data would look like. Furthermore, we were able to freely choose in which programming language we wanted to implement each system. That is why it was possible to implement our systems in different languages, i.e. JAVA, Flash ActionScript 3.0 and Free Pascal.

CARS – Configurable Automotive Research Simulator

In section 2.6, we expatiated on methods for supporting the "Evaluate" stage of the automotive user interface design process. Different kinds of driving simulators were also presented. With CARS, presented in section 6.5, we contributed to the field of fixed-base low-cost driving simulators by providing an open source software that can be downloaded at https://svn.pcuie.uni-due.de/CARS/. The hardware required for realizing a driving simulator with the software are a consumer PC, a gaming steering wheel, and a gaming brake-and-gas-pedal. The CARS software consists of three main components: 1) a map editor that enables experimenters to create a virtual driving environment according to their requirements, 2) a simulation component that renders the view of the created 3D world from a driver's perspective, and 3) an analysis tool that provides a graphical representation of the driven course and calculates a set of statistics that give indications about the driving performance, e.g. mean distance to the racing line and mean speed.

An extended version of CARS also incorporates gaze data. During the driving task, participants' gaze is recorded, and based on this data, the analysis tool calculates measures of distraction, e.g. the eyes-off-road time, which is an indicator of visual distraction. Furthermore, the graphical representation of the driven course indicates when a driver looked at the driving environment and when he looked at other displays or objects in the car. Correlations between driving performance and gaze data can therefore be made directly.

So far, CARS aims at supporting early stages of the design process when initial ideas of automotive user interfaces are implemented in early prototypes and need to be compared and tested. It is designed to give the first indications about the user interface's effect on driver distraction and to provide a basis for deciding which idea is worth pursuing.

7.1.2 Multimodal, Implicit and Gaze-based Interaction in the Car

Exploring multimodal interaction in the car

Providing multimodal input and output opportunities in the desktop domain was only a matter of time. It helps to make our daily work faster and more efficient. The users have the freedom to choose which input device they want to use to interact with the system. For example, they can use the mouse, keyboard shortcuts or even speech recognition to trigger the same function. Output information and feedback are provided through different channels. For example, acoustic warning signals and color changes in the visual representation of a running program in the taskbar indicate that this program requires user's attention.

One central goal of the automotive user interface designer is to develop interfaces in a way that drivers are able to interact with them while driving in an efficient and safe manner. Thus, it is not surprising that multimodality found its way into the car. For example, a radio station can be changed by using buttons mounted on the steering wheel or in the vertical center stack, as well as by speech recognition. The drivers are able to interact with the system in a way that is appropriate for them in a given situation. Multimodal output is for example the current method to present navigation instructions to the driver. Usually, audio is combined with visual representations.

We presented two case studies that contribute to research in the field of multimodal input and output in the car. The steering wheel is the focus of both case studies and they are both more or less related to the navigational context. We developed two prototypes of steering wheels, one that uses vibration output to instruct the driver when and which way to turn and another that supports handwritten input on a display mounted in the middle of the steering wheel.

With the vibrating steering wheel prototype described in section 4.3, we compared different single and multimodal types of output, including visual, audio and vibro-tactile, in two user studies. Results showed that vibro-tactile feedback combined with visual output or audio output led to improved driving performance. Additionally, our participants preferred bimodal output that included vibration over single modal output and the combination of audio and visual output. The vibro-tactile signal provided directional clues by activating the vibration on the left or right side of the steering wheel. Some of the participants relied solely on these instructions and never checked the information on the other channel. Others treated the vibration more as a cue to subsequently check or confirm the information on the additional channel. One might speculate that in the combination visual+audio the audio would take the role of an attention grabber. That is probably true, but audio was often mentioned by the participants as disruptive, e.g. when engaged in a conversation or listening to music, whereas vibration is rather unobtrusive.

An additional and, in our opinion, more natural and flexible input possibility was the focus of the second case study presented in section 4.4. Text input in the car is usually performed by using onscreen keyboards operated by touch or an A-Z speller operated by a multifunctional controller. So far, these input devices are fixed-mounted and have to be operated by the right hand in left-hand drive vehicles and by the left hand in right-hand drive vehicles. By installing a display at the middle of the steering wheel for handwriting input, we leave it to the drivers to choose with which hand they want to provide input to the system. We compared this input position to input in the horizontal center stack. The visual output was provided either on the input display or on a dashboard display close to the speedometer. User study results indicate that handwriting on the steering wheel does not negatively affect the driver's ability to steer the car and that participants perform less errors while writing text on the steering wheel than on the display in the center stack. Half of the participants preferred visual output on the steering wheel and half on the dashboard display. In keeping with the spirit of multimodality, we suggested providing feedback at both positions, so that the driver can decide where he wants to get the feedback.

Exploring implicit interaction and gaze-based interaction in the car

A user interacts implicitly with a system when an action he performs is understood by a computerized system as input without being the primary aim of the user [Schmidt 2000]. Tracking users' eyes is one opportunity for realizing implicit interaction. Furthermore, eye tracking provides a means for a more natural way to interact with an in-car system. With the three case studies reported in chapter 5, we contribute to the relatively new research fields of implicit interaction and gaze-based interaction in the car.

With our *Gazemarks* concept (see section 5.3), we provide an approach to ease attention switching that is not only applicable in the car domain but also in the desktop domain. *Gazemarks* are automatically created visual placeholders based on users' gaze. A placeholder highlights the user's last gaze positions on a display before his attention shifts away from the display. *Gazemarks* should help users resume interrupted tasks more quickly after switching their attention back to the display. Although our initial idea came from observations of how drivers mark positions on a physical map lying on the passenger seat, we first focused on using this concept in a stationary condition.

We designed and developed a prototype that allows *Gazemarks* to be drawn on any given background, e.g. a static image or a running program. Thus, *Gazemarks* can be applied uniformly in both the desktop domain and in the driving context. Results of a user study evaluating the *Gazemarks* concept in a stationary situation show that users are about 3 times faster in solving a simple search task while using *Gazemarks* than without.

While developing the *Gazemarks* prototype, we learned some important lessons that might be useful in other research contexts. Here is a summary of these lessons:

8. For the *Gazemarks* concept, it was essential to determine the duration of a conscious gaze fixation to avoid highlighting a position that the user only inadvertently glanced at on the way away from the display. Our measurements revealed that a user has to gaze longer than 0.13 seconds at a specific area to indicate that this position merited being highlighted.
9. Blinks have to be ignored by the *Gazemarks* system. The duration of a blink is approximately 0.3 to 0.4 seconds. *Gazemarks* only highlight gaze positions after a period of 0.6 seconds in which no other gaze is detected on the screen. Thus, this system does not mark gaze positions corresponding to blinks, which would have made the user experience very confusing.
10. Highlighting an area around the last gaze position instead of marking a single point compensates for the inaccuracy caused by the eye tracker and environmental conditions.

In the second case study, we explored gaze-based interaction as an alternative approach to “hands-free” interaction in the car (see section 5.4). The idea was to make use of the driver’s gaze at a display to ascertain its content directly for highlighting the selectable items, e.g. menu items or music titles. For selecting the item, the user had to push a button on the steering wheel. In a user study, we compared this approach to touch interaction and speech recognition. Our results showed that gaze-based interaction led to the worst and speech recognition to the best driving performance. The most tasks could be performed in the touch condition and the least in the speech condition. Furthermore, participants stated that speech recognition was the most useful, least distracting and easiest way to provide input to the system and allowed them to leave their hands on the steering wheel.

Participants had both interest in and concerns about gaze-based interaction. The main objection was that if the system is not accurate enough it would distract too much from driving. Some accuracy problems could already be observed during the study. Participants sometimes exclaimed “But I looked at it!” when the system did not appear to react to their gaze. This problem was also reflected in the fact that the most errors were performed in that condition. Accuracy plays an important role for eye-based interaction in the car, because inaccuracy might force the user to spend more time on the tertiary task than necessary, which would mean they would be paying less attention to driving.

During our experiment, we learned an important lesson about eye tracking in a car setup: “forcing” the driver to look at a screen in a way that does not reflects his natural behavior decreases recognition accuracy and might thereby taint the evaluation results. A Wizard-of-Oz approach would help avoid having the technical setup influence the results. However, this is obviously not a practical way to evaluate gaze-based interaction. Instead, we recommend using a more flexible eye tracker that fits better to the driving context than the one we used in our studies. Aside from these technical considerations, we also need to consider the possibility that gaze-based interaction – at least in the way we used it – might not be acceptable in the driving context.

In the third case study related to implicit and gaze-based interaction in the car, we focus on an opportunity for face-to-face communication while driving without the need for the driver to turn his head away from the forward roadway (see section 5.5). We developed a driver-passenger video link system that provides a video image of the passengers to the driver, either on a display mounted in the horizontal center stack or on a head-up display. Passengers are also shown a video image of the driver. For the head-up display, we suggested a gaze-based interaction. When the driver looks directly at the head-up area, the image of the passenger is shown with full intensity, and when the driver looks away from the image, it fades to an intensity of 10%. This interaction provides the driver with visual awareness of the passengers without turning towards them or obstructing the forward roadway view.

Results from a user study performed with this video system showed that it could provide drivers with a more natural communication (with greater visual contact) in the car without negatively affecting driving performance. The gaze-based interaction received positive feedback from 11 of our 16 participants and half of the participants would be interested in using a system like the head-up video system in the future. Our proposed gaze-based head-up interaction might be practical in other contexts as well, e.g. navigation information could be switched on and off in a similar way.

7.2 Future Work

Extending CARS

We designed CARS to be a low-cost open source simulation software that is able to estimate the effect of a tertiary task on driving performance, and our evaluation studies strongly indicate its effectiveness. Nevertheless, more comprehensive user tests are required to verify its reliability. It might be adequate to compare results obtained when using CARS versus when using LCT [Mattes 2003], since LCT's validity was demonstrated by experiments performed with the LCT software as well as in a high-fidelity driving simulator. However, CARS offers more flexibility in the creation of a virtual world and the design of the driving task, and we therefore aim to directly compare CARS with high-fidelity driving simulators or real driving situations in future user studies.

Towards a single distraction factor for assessing driver distraction

With LCT, a first step towards a commonly-used distraction factor was already taken. We suggest including more indications of distraction into this factor other than those measuring driving performance. Visual attention measures, e.g. eye tracking data, and stress level measures, e.g. physiological data, can also offer valuable clues about driver distraction. Another important element that has to be considered for the distraction factor is task performance. While analyzing results gained in our user studies, we were often confronted with how to interpret tertiary task performance in relation to driving performance. In many cases, we had to deal with the fact that some participants performed more tertiary tasks and drove worse, while others performed fewer tasks and drove better. This observation begs the question “Is it safer to be less distracted over a longer period of time or to be more distracted over a shorter period of time?”

Tool support for creating design spaces for driver-based automotive user interfaces

So far, our proposed design space for driver-based automotive user interfaces provides a means for adding stationary input and output devices to the graphical representation in order to analyze existing user interfaces or document new interface ideas. For future work, we envision a software tool that assists designers in choosing and placing controls into the design space. The idea is that designers specify input and output devices in a picture or in a design sketch, from which a graphical representation could automatically be generated. The tool might also provide an immediate estimation of the control placement’s impact on the driver, e.g. with regard to visual load or cognitive load. Additional measures that detect potential design flaws, which would impact driving performance, should also be included and could possibly be automatically determined.

Eye-based interaction with head-up displays

Using eye tracking for interacting with a head-up display offers new opportunities to make interaction with in-car systems more natural and shall be investigated in more detail.

Multimodal steering wheel

In studies with our vibrating steering wheel prototype, which has six integrated vibration motors, we found that in addition to a static signal, a dynamic signal that runs along the steering wheel has potential for communicating turn instructions. We already discussed building a second steering wheel with smaller vibration motors that are closer together so that drivers could feel vibrations from more motors on the wheel. Our first studies using a line of vibration motors mounted on a glove showed that participants are good at recognizing in which direction a signal moves [Bial et al. 2011]. Further studies are needed to evaluate use of these vibration patterns while driving. However, tactile feedback does not necessarily have to be vibro-tactile, and other tactile output forms should also be considered. Some of our initial ideas include using air blasts aimed at the palm through small holes in the steering wheel or using temperature changes for less time-critical events.

For exploring input opportunities on a steering wheel, we built a multi-touch steering wheel for gestural interaction [Döring et al. 2011]. With this steering wheel, input is possible on the entire surface, which offers room for investigating handwriting interaction further. For example, thumbs could be used for writing on the surface, allowing the hands to remain on the steering wheel.

Using the steering wheel for input and output always brought up the issue of whether the interaction surface should be fixed or should rotate with the steering wheel. In our studies, the surface always rotates with the steering movement. User studies with a fixed surface might see different results.

7.3 Concluding Remarks

In the endeavor of this dissertation, many open questions in the exciting research field of Human Computer Interaction within the car (automotive HCI) emerged. I expect that this research field will become even more exciting in the future when the additional of more and more driver assistance tools and systems pave the way towards fully automated driving. Together with new technologies and legal requirements, a new dynamic space for innovation will be created that offers many opportunities for new forms of interaction in the car.

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9 Appendix

9.1 Example Consent Form - English

I, ______________________ (print name)

agree to participate in this research project.

I have had the purposes of the study explained to me.

I have been given the opportunity to ask questions about the study and have had these answered satisfactorily

I have been informed that I may refuse to participate at any point by simply saying so.

I have been assured that my confidentiality will be protected.

I agree that the information that I provide can be used for educational or research purposes, including publication

I O do (please mark)

O do not

agree that still images of myself can be used in presentations and publications, which may appear online

I understand that if I have any concerns or difficulties I can contact:

Dagmar Kern at dagmar.kern@uni-due.de

Signed: ______________________ Date: __________

9.2 Example Consent Form - German

Ich ______________________________ stimme der Teilnahme an diesem Forschungsprojekt zu.

Mir wurde der Zweck dieser Studie erklärt.

Ich habe die Möglichkeit während der Studie Fragen zu stellen, welche zufriedenstellend beantwortet werden müssen.

Ich wurde darüber informiert, dass ich zu jeder Zeit den Versuch abbrechen kann.

Mir wurde versichert, dass meine Daten vertraulich behandelt werden.

Ich stimme zu, dass die von mir gegebenen oder über mich gesammelten (Fahr-) Informationen für Lehr- und Forschungszwecke genutzt werden dürfen.

Ich O stimme zu (bitte ankreuzen)

O stimme nicht zu,

dass Bilder von mir in Präsentationen und Veröffentlichungen (welche auch online erscheinen können) verwendet werden dürfen.

Mir ist bewusst, dass wenn ich irgendwelche Bedenken oder Fragen habe, ich mich an Dagmar Kern (dagmar.kern@uni-due.de) wenden kann

Essen, den Unterschrift:

_____________________ ____________________________________

9.3 Case Study 1: Tactile Output Embedded into the Steering Wheel

9.3.1 User Study 1 – Questionnaire

1. Age:____

2. Gender: O female O male

3. How long have you had a driving licence? ________________________

4. Roughly, how many miles do you drive per year? ____________________

5. Do you drive

   O less than once a week O 1 to 4 times a week O 5 to 7 times a week

6. Do you use a navigation system? (e.g. GPS)

   O yes O no (go to question number 10)

7. In which cases is the voice output of the navigation system inappropriate or even disturbing for you? (Check as many as apply)

   O while talking to people in the car.

   O while listening to the radio

   O other (please specify)________________________________

8. In which cases do you turn off the voice output of the navigation system? (Check as many as apply)

   O while talking to people in the car.

   O while listening to the radio

   O other (please specify)________________________________

9. How often do you miss a turn, because the voice output was turned off or you didn't notice it? (e.g. when other people in the car are talking to you) Please specify your choice by drawing a cross in the line.

   very often |____________________| never

10. During the experiment, which one of the presented output signals did you prefer?

   ○ Sound
   ○ Vibration
   ○ Vibration + Sound

11. To what extent were the following signals pleasant? Please specify your choice by drawing a cross in the line.

	very	not at all
sound	├─────────────┤	
vibration	├─────────────┤	
sound+vibration	├─────────────┤	

Comments:____

____

12. To what extent were the following signals annoying? Please specify your choice by drawing a cross in the line.

	very	not at all
sound	├─────────────┤	
vibration	├─────────────┤	
sound+vibration	├─────────────┤	

Comments:____

____

13. To what extent were the following signals distracting? Please specify your choice by drawing a cross in the line.

	very	not at all
sound	├	┤
vibration	├	┤
sound+vibration	├	┤

Comments:____

____

14. The length of the signals was

	too short	just right	too long
Sound	├		┤
Vibration	├		┤

Comments:____

____

15. What do you think are the advantages of …

… the sound signal output?______________________________________

____

… the vibration signal output?___________________________________

____

… the sound + vibration output?__________________________________

____

16. What do you think are the disadvantages of …

… the sound signal? ____

____

… the vibration signal? ______________________________________

____

… the sound + vibration output? ________________________________

____

17. Any other comments

____

____

____

____

____

____

____

____

____

____

9.3.2 User Study 2 – Fragebogen

1. Alter:______________________________
2. Geschlecht: O weiblich O männlich
3. Wie lange haben Sie Ihren Führerschein?____________________
4. Wie viele Kilometer fahren Sie im Jahr? ca.:____________________
5. Wie häufig fahren Sie mit dem Auto?

   O weniger als ein mal wöchentlich

   O 1 bis 4 mal wöchentlich

   O 5 bis 7 mal wöchentlich
6. Benutzen Sie ein Navigationssystem? (z.B. GPS)

   O ja O nein (weiter mit Frage 10)
7. In welchen Situationen empfinden Sie die Sprachausgabe Ihres Navigationssystem als unangebracht / störend? (Mehrfachnennungen möglich)

   O während einer Unterhaltung im Auto

   O beim Radio hören

   O andere ______________________________
8. In welchen Situationen schalten Sie die Sprachausgabe des Navigationssystems ab? (Mehrfachnennungen möglich)

   O während einer Unterhaltung im Auto

   O beim Radio hören

   O andere______________________________
9. Wie häufig konnten Sie einer Navigationsanweisung nicht folgen, weil Sie die Anweisung akustisch nicht verstanden haben oder der Ton ausgeschaltet war? (z.B. wenn Sie sich mit anderen Personen im Auto unterhalten). Bitte markieren Sie Ihre Einschätzung auf der Linie.

   Sehr häufig |————————————| niemals

10. Welche der vorgestellten Ausgabeformen gefällt Ihnen am besten, welche überhaupt nicht? Bitte bringen Sie die Ausgabeformen in eine Reihenfolge von 1-5. (1 = gefällt mir am besten bis 5 = gefällt mir überhaupt nicht.)

__ Visuelle Darstellung

__ Audio Ausgabe

__ Visuelle Darstellung + Audio Ausgabe

__ Visuelle Darstellung + Vibration

__ Audio Ausgabe + Vibration

Kommentare:

____

____

11. Zu welchem Grad haben Sie die Ausgabeformen als angenehm empfunden? Bitte markieren Sie Ihre Einschätzung auf der Linie.

	sehr	überhaupt nicht
visuelle Darstellung	|——————————|	
Audio Ausgabe	|——————————|	
visuelle Darstellung + Audio Ausgabe	|——————————|	
Visuelle Darstellung + Vibration	|——————————|	
Audio Ausgabe + Vibration	|——————————|	

Kommentare:

____

____

12. Zu welchem Grad haben Sie die Ausgabeformen als ärgerlich / nervig empfunden? Bitte markieren Sie Ihre Einschätzung auf der Linie.

	sehr	überhaupt nicht
Visuelle Darstellung		
Audio Ausgabe		
Visuelle Darstellung + Audio Ausgabe		
Visuelle Darstellung + Vibration		
Audio Ausgabe + Vibration		

Kommentare:

13. Zu welchem Grad haben Sie die Ausgabeformen als ablenkend von der Fahraufgabe empfunden Bitte markieren Sie Ihre Einschätzung auf der Linie.

	sehr	überhaupt nicht
Visuelle Darstellung		
Audio Ausgabe		
Visuelle Darstellung + Audio Ausgabe		
Visuelle Darstellung + Vibration		
Audio Ausgabe + Vibration		

Kommentare:

14. Die Länge der Ausgabeform war

	zu kurz	zu lang
Audioausgabe		
Visuelle Darstellung		
Vibration		

Kommentare:

15. Welche Vorteile sehen Sie …

… in der visuellen Darstellung?

…in der Audioausgabe?

… in der Kombination visuelle Darstellung und Audioausgabe?

… in der Kombination visuelle Darstellung und Vibration?

… in der Kombination Audioausgabe und Vibration?

16. Welche Nachteile sehen Sie …

… in der visuellen Darstellung?^

… in der Audioausgabe?

… in der Kombination visuelle Darstellung und Audioausgabe?

… in der Kombination visuelle Darstellung und Vibration?

… in der Kombination Audioausgabe und Vibration?

17. Weitere Kommentare

Vielen Dank für Ihre Teilnahme!

9.4 Case Study 2: Handwriting Text Input while Driving

9.4.1 Protokoll 1 für Teilnehmer ID 1

1.	<1min	Bedienung der Applikation ohne Fahren		
2.	5 min	Testfahrt mit Simulator ohne Bedienung der Applikation und ohne Messung der Daten		
3.	5 min	Erste Messung ohne Bedienung der Applikation		
4.	5 min	**Eing. Lenkrad**	**Ausg. Lenkrad**	**mit Namenssatz 1**
5.	5 min	**Eing. Mittelkonsole**	**Ausg. Mittelkonsole**	**mit Namenssatz 2**
6.	5 min	**Eing. Lenkrad**	**Ausg. Tacho**	**mit Namenssatz 3**
7.	5 min	**Eing. Mittelkonsole**	**Ausg. Tacho**	**mit Namenssatz 4**

Bemerkung:

9.4.2 Fragebogen

1. Geschlecht — ❑ männlich ❑ weiblich
2. Wie alt sind Sie? ____________________
3. Haben Sie einen Führerschein? — ❑ ja ❑ nein

   Wenn ja, seit wann? ____________________
4. Welche Schreibart verwenden Sie? — ❑ Schreibschrift ❑ Druckschrift
5. Arbeiten Sie mit Touchscreens? — gar nicht |———————| regelmäßig
6. Spielen sie Rennsimulationen am PC? — ❑ ja ❑ nein
7. Verwenden Sie ein Navigationssystem beim Fahren? — ❑ ja ❑ nein

   Wenn ja, bedienen Sie es

   Über ein Touchscreen? — ❑ ja ❑ nein
8. Wie viele km fahren sie durchschnittlich im Jahr?
   - ❑ Unter 10.000 km
   - ❑ 10.000-20.000 km
   - ❑ 20.000-30.000 km
   - ❑ über 30.000 km
9. Wie oft fahren Sie in der Woche?
   - ❑ Weniger als 1mal
   - ❑ 1-4 mal
   - ❑ 5-7 mal

10. Sortieren Sie die folgenden Eingabe/Ausgabe -Möglichkeiten nach Zahlen von 1 - 4, wobei die Zahl 1 der von Ihnen am meisten bevorzugten Möglichkeit entspricht.
    - ☐ Mittelkonsole/Mittelkonsole
    - ☐ Mittelkonsole/Tacho
    - ☐ Lenkrad/Lenkrad
    - ☐ Lenkrad/Tacho

11. Zu welchem Grad haben die folgenden Eingabe/Ausgabe–Möglichkeiten Sie abgelenkt?

Mittelkonsole/Mittelkonsole	stark	gar nicht
Mittelkonsole/Tacho	stark	gar nicht
Lenkrad/Lenkrad	stark	gar nicht
Lenkrad/Tacho	stark	gar nicht

12. Zu welchem Grad fanden Sie die folgenden Eingabe/Ausgabe-Möglichkeiten angenehm?

Mittelkonsole/Mittelkonsole	gar nicht	sehr
Mittelkonsole/Tacho	gar nicht	sehr
Lenkrad/Lenkrad	gar nicht	sehr
Lenkrad/Tacho	gar nicht	sehr

13. Welche Eingabemöglichkeit fanden Sie am angenehmsten?
    - ❑ Mittelkonsole
    - ❑ Lenkrad
14. Welche Ausgabemöglichkeit fanden Sie am angenehmsten?
    - ❑ Mittelkonsole
    - ❑ Tacho
    - ❑ Lenkrad
15. Welche Vorteile sehen Sie bei der Eingabe Mittelkonsole/Mittelkonsole?

___

___

16. Welche Vorteile sehen Sie bei der Eingabe Mittelkonsole/Tacho?

___

___

17. Welche Vorteile sehen Sie bei der Eingabe Lenkrad/Lenkrad?

___

___

18. Welche Vorteile sehen Sie bei der Eingabe Lenkrad/Tacho?

___

___

19. Welche Nachteile sehen Sie bei der Eingabe Mittelkonsole/Mittelkonsole?

20. Welche Nachteile sehen Sie bei der Eingabe Mittelkonsole/Tacho?

21. Welche Nachteile sehen Sie bei der Eingabe Lenkrad/Lenkrad?

22. Welche Nachteile sehen Sie bei der Eingabe Lenkrad/Tacho?

23. Kommentar:

9.5 Case Study 3: *Gazemarks* - Gaze-Based Visual Placeholders to Ease Attention Switching

9.5.1 User Study 1: Fragebogen

Allgemein

1. Alter:____
2. Geschlecht:

   O weiblich   O männlich

3. Tragen Sie eine Sehhilfe?

   O nein   O Brille   O Kontaktlinsen

4. Wie häufig nutzen Sie ein Navigationssystem? (z.B. GPS)

   O nie

   O weniger als 1mal pro Monat

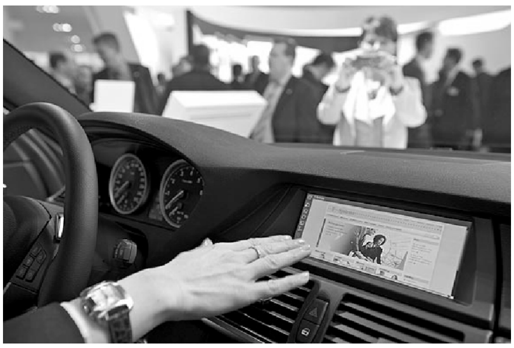
   O 4-5mal pro Monat

   O 1-5mal pro Woche

   O täglich

5. Besitzen Sie ein „multimodales“ Display im Auto?

   O ja   O nein



Beispiel: „multimodales“ Display

6. Bringen Sie die Konzepte in die Reihenfolge, abhängig davon, wie gut Sie Ihnen gefallen haben. Ordnen Sie den Konzepten die Zahlen 1-4 zu. (Jede Zahl nur einmal, 1 am besten, 4 am schlechtesten)

   ___ ohne Fähnchen

   ___ mit rotem Fähnchen

   ___ mit Lupe

   ___ mit Verlauf-Lupe

Darstellung der Suchhilfen

7. Wie gut konnten sie die Buchstaben und die Zahlen auf der Karte lesen?

   sehr schlecht |————————| sehr gut

8. Wie empfinden Sie die Genauigkeit der Darstellung der Suchhilfe zur Position Ihres Blickes?

   sehr ungenau |————————| sehr genau

9. Betrachten Sie, den Einsatz einer Suchhilfe generell als sinnvoll?

   völlig sinnlos |————————| sehr sinnvoll

10. Welche Vorteile sehen Sie in der Such-Unterstützung

____

____

____

11. Welche Nachteile sehen Sie in der Such-Unterstützung

____

____

____

12. Hat Ihnen die Darstellung des Fähnchens zugesagt?

O ja,weil

____

____

O nein, warum nicht

____

____

13. Hat Ihnen die Darstellung der Lupe zugesagt?

O ja, weil

____

____

O nein, warum nicht

____

____

14. Hat Ihnen die Darstellung der Verlauf-Lupe zugesagt?

O ja, weil

____

____

O nein, warum nicht

____

____

15. Wie hilfreich war das Fähnchen beim Suchen?

gar nicht hilfreich |———————| sehr hilfreich

16. Wie hilfreich war die Lupe beim Suchen?

gar nicht hilfreich |———————| sehr hilfreich

17. Wie hilfreich war die Verlauf-Lupe beim Suchen?

gar nicht hilfreich |———————| sehr hilfreich

18. Welche Darstellungsmöglichkeit einer Suchhilfe könnten sie sich noch vorstellen.

____

____

____

19. Weitere Kommentare

____

____

____

____

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Vielen Dank für Ihre Teilnahme!

9.5.2 User Study 2: Fragebogen

Allgemein

1. Alter:____
2. Geschlecht:

   O weiblich　　　O männlich

3. Tragen Sie eine Sehhilfe?

   O nein　　O Brille　　O Kontaktlinsen

4. Wie häufig nutzen Sie ein Navigationssystem? (z.B. GPS)

   O nie

   O weniger als 1mal pro Monat

   O weniger als 3mal pro Monat

   O 1-5mal pro Woche

   O täglich

5. Besitzen Sie ein „multimodales“ Display im Auto?

   O ja　　O nein

Beispiel: „multimodales“ Display

6. Hat Ihnen die Darstellung der Lupe zugesagt?

   O ja, weil____

   ____

   O nein, warum nicht ____

   ____

7. Wie hilfreich war die Lupe beim Suchen

   Gar nicht hilfreich |———————| sehr hilfreich

8. Wie gut konnten sie die Buchstaben und die Zahlen auf der Karte lesen?

   sehr schlecht |———————| sehr gut

9. Wie empfinden Sie die Genauigkeit der Darstellung der Suchhilfe zur Position Ihres Blickes?

   sehr ungenau |———————| sehr genau

10. Betrachten Sie, den Einsatz einer Suchhilfe generell als sinnvoll?

    völlig sinnlos |———————| sehr sinnvoll

11. Welche Vorteile sehen Sie in der Such-Unterstützung

____

____

____

12. Welche Nachteile sehen Sie in der Such-Unterstützung

____

____

____

13. Welche Darstellungsmöglichkeit einer Suchhilfe könnten sie sich noch vorstellen.

____

____

____

14. Weiter Kommentare

____

____

____

____

____

____

____

____

Vielen Dank für Ihre Teilnahme!

9.6 Case Study 4: Making Use of Drivers' Glances onto the Screen

9.6.1 Teilnehmerinformation

Forschungszweck:

In diesem Experiment untersuchen wir die Verwendung verschiedener Modalitäten für die Texteingabe im Fahrzeug. Hierbei interessiert uns die Auswirkung auf die Fahrleistung, die Umsetzung der Texteingabe an sich und das subjektive Empfinden des Fahrers. Hierfür wird das Fahrverhalten und das Blickverhalten aufgezeichnet, die Texteingabe erfasst und es werden verschiedene Fragebögen verwendet.

Freiwilligkeit:

An diesem Forschungsprojekt nehmen Sie freiwillig teil. Ihr Einverständnis können Sie jederzeit und ohne Angabe von Gründen widerrufen.

Datenschutz

Die Universität Duisburg-Essen und das DFKI (Kooperationspartner in diesem Projekt) misst den Belangen des Datenschutzes große Bedeutung bei. Unsere diesbezüglichen Verfahrensabläufe stehen in Einklang mit den maßgeblichen deutschen Datenschutzgesetzen und den Bestimmungen. Mit Teilnahme am Experiment erkläre ich mich einverstanden, dass personenbezogene Daten und Aufzeichnungen zur Auswertung des Experimentes gesammelt werden. Die Daten werden hierbei anonymisiert gespeichert. Die während des Experimentes gesammelten, personenbezogenen Daten und Aufzeichnungen werden ausschließlich im Rahmen des Experimentes genutzt. Eine Weiterleitung an Dritte oder eine andersartige Verwertung findet nicht statt.

Hiermit bestätige ich, dass ich diese Datenschutzrichtlinie gelesen habe und akzeptiere. Ich erkläre mich damit einverstanden, dass die von mir gesammelten Daten, gemäß dieser Richtlinie im Experiment verwendet werden.

Ort/Datum/ Unterschrift

9.6.2 Fragebogen

Die Auswertung Ihrer Antworten erfolgt anonym. Bitte geben Sie ehrliche und objektive Antworten.

A: Allgemeine Angaben:

Geschlecht: Männlich ☐ Weiblich ☐

Alter: _______

Sie sind Brillenträger?: ja ☐ nein ☐ Kontaktlinsen ☐

Beruf: ______________________________

Jahre mit Führerschein: _____ Jahre

Fahrleistung pro Jahr: 0 bis 10.000 km ☐ 10.001 bis 25.000 km ☐ mehr als 25.000 km ☐

Sie sind: Linkshänder ☐ Rechtshänder ☐ Beidhändig ☐

Wie viele Stunden pro Woche verbringen Sie ungefähr vor dem Computer?

Privat ____________ beruflich________________________

Wie groß ist Ihr Interesse an moderner Technik generell? (z.B. Handy, PC, digitaler Assistent, digitale Küche)

☐	☐	☐	☐	☐
1	**2**	**3**	**4**	**5**
sehr gering	**eher gering**	**mittelmäßig**	**eher groß**	**sehr groß**

Wie viel Erfahrung haben Sie mit moderner Technik?

☐	☐	☐	☐	☐
1	**2**	**3**	**4**	**5**
sehr gering	**eher gering**	**mittelmäßig**	**eher groß**	**sehr groß**

B: Bedingung Nr 1: Touch

1. Wie hoch waren die Anforderungen an die globale Aufmerksamkeit?

(Erklärung: Insgesamt alle mentalen (denken, entscheiden…), visuellen und auditiven Faktoren, die insgesamt während des Versuchs erforderlich sind, um die Gesamtleistung zu erzielen)

Gering → ***Hoch***

☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

2. Wie hoch waren die visuellen Anforderungen?

(Erklärung: Visuelle Faktoren, die während des Versuchs erforderlich sind, um die Gesamtleistung zu erzielen (alles, was mit dem Sehen zu tun hat))

Gering → ***Hoch***

☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

3. Wie hoch waren die auditiven Anforderungen?

(Erklärung: Auditive Faktoren, die während des Versuchs erforderlich sind, um die Gesamtleistung zu erzielen (alles, was mit Gehörtem zu tun hat))

Gering → ***Hoch***

☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

4. Wie hoch waren die manuellen Anforderungen?

(Erklärung: Manuelle Faktoren, die während des Versuchs erforderlich sind, um die Gesamtleistung zu erzielen (alles, was mit der Handhabung zu tun hat))

Gering	→				*Hoch*
☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

5. Wie stark war das Stressniveau?

(Erklärung: Stress Niveau während des Versuchsablaufs wie Irritation, Müdigkeit, Unsicherheit, Entmutigung, etc.)

Gering	→				*Hoch*
☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

6. Wie hoch war die zeitliche Anforderung?

(Erklärung: Gefühlte Belastung und spezifische Beeinträchtigung durch die schnelle Abfolge der Aufgaben)

Gering	→				*Hoch*
☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

7. Wie stark war der Interferenzfaktor?

(Erklärung: Beeinträchtigung des Fahrerzustandes und Auswirkungen auf die Fahrleistung durch die gleichzeitige Zweitaufgabe Textbearbeitung während des Fahrens)

Gering → ***Hoch***

☐	☐	☐	☐	☐	☐
0	**1**	**2**	**3**	**4**	**5**

C: Allgemeine Befragung:

Die Fahrsituation war realistisch.

□ 1	□ 2	□ 3	□ 4	□ 5	□
Stimme nicht zu	stimme eher nicht zu	teils, teils	stimme eher zu	stimme zu	keine Angabe möglich

Insgesamt war es leicht, Aufgaben während der Fahrt zu bewältigen.

□ 1	□ 2	□ 3	□ 4	□ 5	□
stimme nicht zu	stimme eher nicht zu	teils, teils	stimme eher zu	stimme zu	keine Angabe möglich

Es war schwierig, während des Fahrens den Text einzugeben mithilfe ...

	1 stimme nicht zu	2 stimme eher nicht zu	3 teils, teils	4 stimme eher zu	5 stimme zu
... der **Sprachsteuerung.**	□	□	□	□	□
... des **Touchscreens.**	□	□	□	□	□
... des **Eyetrackers.**	□	□	□	□	□

Vom Fahren lenkte mich vor allem die Texteingabe mithilfe **...** ab.

	→				
	1 **stimme nicht zu**	**2** **stimme eher nicht zu**	**3** **teils, teils**	**4** **stimme eher zu**	**5** **stimme zu**
... der **Sprachsteuerung.**	☐	☐	☐	☐	☐
... des **Touchscreens.**	☐	☐	☐	☐	☐
... des **Eyetrackers.**	☐	☐	☐	☐	☐

Im Fahrzeug finde ich persönlich besonders nützlich: Die Verwendung **...**

	→				
	1 **stimme nicht zu**	**2** **stimme eher nicht zu**	**3** **teils, teils**	**4** **stimme eher zu**	**5** **stimme zu**
... der **Sprachsteuerung.**	☐	☐	☐	☐	☐
... des **Touchscreens.**	☐	☐	☐	☐	☐
... des **Eyetrackers.**	☐	☐	☐	☐	☐

Für meinen eigenen Wagen würde ich mir gegen Aufpreis auswählen: **...**

	1 stimme nicht zu	2 stimme eher nicht zu	3 teils, teils	4 stimme eher zu	5 stimme zu
... der **Sprachsteuerung.**	☐	☐	☐	☐	☐
... des **Touchscreens.**	☐	☐	☐	☐	☐
... des **Eyetrackers.**	☐	☐	☐	☐	☐

Ich würde die Interaktion mithilfe des Eyetrackers gerne zusätzlich zu anderen Interaktionsmöglichkeiten (z.B. Sprache, Touchscreen, Drehknopf usw) nutzen.

☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Stimme nicht zu	**stimme eher nicht zu**	**teils, teils**	**stimme eher zu**	**stimme zu**	**keine Angabe möglich**

Ich würde den Eytracker gerne ausschließlich zur Bedienung nutzen.

☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
stimme nicht zu	**stimme eher nicht zu**	**teils, teils**	**stimme eher zu**	**stimme zu**	**keine Angabe möglich**

Welche anderen Funktionen im Fahrzeug würden Sie gerne mit dem Eyetracker bedienen können?

- ☐ Musikauswahl
- ☐ Detaileinstellungen am Radio, z.B. Bass
- ☐ Navigationssystem
- ☐ Telefon
- ☐ In einer Darstellung (z.B. Text, Karte) scrollen

Andere:

____

____

____

Mehrfachnennungen möglich:

Welche Art von Bedienung schätzen Sie als besonders **zeitsparend** ein?

☐ Sprache ☐ Touch ☐ Blick

Welche Art von Bedienung schätzen Sie als besonders **interessant** ein?

☐ Sprache ☐ Touch ☐ Blick

Mit welcher Art von Bedienung können Sie besonders **präzise** auswählen?

☐ Sprache ☐ Touch ☐ Blick

Welche Art von Bedienung schätzen Sie als besonders **stressfrei** ein?

☐ Sprache ☐ Touch ☐ Blick

Welche Art von Bedienung schätzen Sie als besonders **bequem** ein?

☐ Sprache ☐ Touch ☐ Blick

Welche Art von Bedienung schätzen Sie als besonders **intuitiv (leicht erlernbar)** ein?

☐ Sprache ☐ Touch ☐ Blick

Was fanden Sie **besonders gut** bei der Verwendung .....

... der Sprache?

... des Touchscreens?

... des Eyetrackers?

Was fanden Sie besonders **schlecht** bei der Verwendung ....

... der Sprache?

... des Touchscreens?

... des Eyetrackers?

Haben Sie weitere Anregungen oder Kritikpunkte?

9.7 Case Study 5: Supporting Face-to-face Communication in the Car

9.7.1 Fragebogen

1. Besitzen Sie einen Führerschein? ◯ Ja ◯ Nein
2. Wie alt sind Sie? __________
3. Geschlecht: ◯ Männlich ◯ Weiblich
4. Seit wie vielen Jahren haben Sie den Führerschein? __________
5. In welchem Land fahren Sie hauptsächlich? ______________________________
6. Wie oft fahren Sie?
   Bitte wählen Sie nur eine der folgenden Antworten aus:

   ◯ < 1 Tag in der Woche ◯ 1-4 Tage in der Woche ◯ 5-7 Tage in der Woche
7. Wie häufig fahren Sie mit anderen Personen im Auto?
   Bitte wählen Sie nur eine der folgenden Antworten aus:

   ◯ Nie ◯ Selten ◯ Manchmal ◯ Regelmäßig ◯ Oft ◯ Sehr oft
8. Während Sie mit anderen Personen im Auto fahren, wie viel Prozent der Zeit unterhalten Sie sich mit ihnen?
   Bitte wählen Sie nur eine der folgenden Antworten aus:

   ◯ Nie ◯ Selten ◯ Manchmal ◯ Regelmäßig ◯ Oft ◯ Sehr oft

   Bemerkungen:

   ____

   ____
9. Während Sie Auto fahren, nutzen Sie eine Navigationsystem? ◯ Ja ◯ Nein
10. Spielen Sie Computer-Rennspiele? ◯ Ja ◯ Nein
    Wenn ja, welche?

    ____

    ____
11. Haben Sie bereits Erfahrung mit Fahrsimulatoren gemacht? ◯ Ja ◯ Nein
    Wenn ja, welche?

    ____

9.7.2 Feedbackbogen

1. Wenn Sie im Auto fahren, wie verhalten Sie sich, um sich mit Mitfahrern auf dem Rücksitz zu unterhalten:
   a. Ziehen Sie es vor, die Mitfahrer zu sehen? [◯ Ja / ◯ Nein]
   b. Wenn ja, wie erhaschen Sie einen Blick auf den Mitfahrer?

   ____

   ____

2. Während des Versuchs haben Sie verschiedene Fahrsituationen kennengelernt.
   a. Wie angenehm fanden Sie es sich mit den Mitfahrern zu unterhalten in den unterschiedlichen Situationen?

	Sehr unangenehm ↑		Weder noch ↑		Sehr angenehm ↑
Fahrt ohne Video	1	2	3	4	5
Fahrt mit Bildschirm	1	2	3	4	5
Fahrt mit HUD	1	2	3	4	5

   b. Wie schwierig war es für Sie in den unterschiedlichen Situationen zu fahren?

	Nicht Schwierig ↑		Weder noch ↑		Schwierig ↑
Fahrt ohne Video	1	2	3	4	5
Fahrt mit Bildschirm	1	2	3	4	5
Fahrt mit HUD	1	2	3	4	5

3. Sie haben während des Versuchs mit den Mitfahrern in unterschiedlichen Situationen unterhaltet: zweimal ohne Video, zweimal mit Bildschirm und zweimal mit HUD. Welche Situation hat Ihnen am besten gefallen?
   [◯ Unterhaltung ohne Video /◯Unterhaltung mit Bildschirm /◯Unterhaltung mit HUD],

   weil

   ____

   ____

4. Bevorzugen Sie die Kommunikation über den Bildschirm gegenüber Ihrem bisherigen Kommunikationsverhalten im Auto?
[◯ Ja / ◯ Nein], weil

____

____

____

5. Bevorzugen Sie die Kommunikation über den HUD gegenüber Ihrem bisherigen Kommunikationsverhalten im Auto?
[◯ Ja / ◯ Nein], weil

____

____

____

6. In dem Versuch hatten wir den Bildschirm über der Mittelkonsole angebracht (siehe oben). Hat Ihnen diese Position gefallen?
[◯ Ja / ◯ Nein],

weil____

____

7. In dem Versuch hatten wir den HUD am unteren Rand der Windschutzscheibe angebracht (siehe oben). Hat Ihnen diese Position gefallen?
[◯ Ja / ◯ Nein],

weil____

____

8. An welcher anderen Positionen hätten Sie gerne die Bild der Mitfahrern am Rückbank?
   Bitte wählen Sie alle Punkte aus, die zutreffen:

   ☐ In der Nähe des Lenkrades

   ☐ In der Nähe des Rückspiegels

   ☐ Sonstiges: ____

9. In dem Versuch hat die Lichtdurchlässigkeit des HUDs sich nach Ihrem Blick geändert. Wenn Sie nahe an den Bild des HUDs geguckt haben, ist sie opaque geworden. Wenn Sie weg von dem Bild gesehen haben, ist sie lichtschwach geworden. Hat diese Interaktion Ihnen gefallen?

   [◯ Ja / ◯Nein],

   weil____

   ____

   ____

10. Hätten Sie gerne eine andere Interaktionsverhalten mit dem HUD, damit es Ihnen besser gefallen würden?
    [◯ Ja /◯ Nein]

    Wenn ja, bitte beschreiben Sie die hier:_____________________________

    ____

    ____

    ____

11. In dem Versuch haben Sie zwei Video-Systeme kennengelernt, eins mit einem Bildschirm und eins mit einem HUD (projekziertes Bild), während Sie sich mit den Mitfahrern unterhalten haben.
    a. Würden Sie ein ähnliches Video-System <u>mit Bildschirm</u> verwenden?

       [◯Ja / ◯Nein],

       weil____

    b. Würden Sie ein ähnliches Video-System <u>mit HUD</u> verwenden?

       [◯ Ja / ◯ Nein],

       weil____

       ____

Weiter Kommentare zum Versuch/der Anwendung:

____

____

____