Fakultät II – Informatik, Wirtschafts- und Rechtswissenschaften
Department für Informatik

In-Vehicle Ambient Light Displays for Advanced Driver Assistant Systems

Angenommene Dissertation zur Erlangung des Grades und Titels eines
Doktors der Naturwissenschaften (Dr. rer. nat.)

vorgelegt von

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Tag der Disputation: 2. Mai 2019

Zusammenfassung

Advanced Driver Assistant Systems (ADAS), oder Fahrassistenzsysteme, unterstützen Fahrer[1] in einer Vielzahl von Situationen, indem sie Informationen, Warnungen, oder Alarme ausgeben. Es wurden bereits einige Anzeigen und andere Ausgabemodalitäten untersucht. Trotzdem gibt es immer noch eine groSSe Anzahl an Unfällen. In dieser Forschungsarbeit untersuchen wir, ob und wie das Fahrverhalten verbessert werden kann, wenn Fahrern Informationen über peripheres Sehen vermittelt werden. Der Gedanke dahinter ist, dass Fahrer weniger durch eine periphere Anzeige abgelenkt werden, als durch herkömmliche.

Der Fokus dieser Arbeit liegt auf "Ambient Light Displays (ALDs)", oder Lichtanzeigen in der Umgebung, die in im Fahrzeuginnenraum positioniert sind. ALDs gehören zu der Klasse der "Ambient Displays", die Informationen vermitteln, ohne den Fokus der Nutzer zu benötigen. Bisherige Untersuchungen haben gezeigt, dass diese Displays dafür verwendet werden können Nutzer nebenläufig zu informieren, aber auch so entworfen werden, dass sie die Aufmerksamkeit ihrer Nutzer in wichtigen Situation auf sich lenken.

In dieser Arbeit untersuchen wir, wie ALDs und ihre Lichtmuster im PKW für verschiedene Anwendungsfälle umgesetzt werden können. Unsere getesteten Prototypen unterstützen Fahrer beim Navigieren, rückwärts einparken, im sicheren Abstand folgen, und beim Spurwechsel. Daraus haben wir Empfehlungen für zukünftige ALD-basierte Systeme abgeleitet und zukünftige Forschungsrichtungen motiviert. AuSSerdem haben wir anhand der Spurwechselassistenz den Einfluss von ALDs auf das Fahrverhalten und Blickverhalten der Fahrer vertieft untersucht.

Unsere Ergebnisse zeigen, dass ALDs dazu geeignet sind Fahrer in verschiedenen Situationen zu unterstützen. Der Hauptvorteil von ALDs liegt darin, dass Informationen effektiv kommuniziert werden können, ohne Fahrer visuell abzulenken. Allerdings, konnten wir auch beobachten, dass schlechte Lichtmuster das Fahrverhalten verschlechtern und dass trotz der nebenläufigen Darstellung der Information Reaktionszeiten nicht besonders stark reduziert werden. Zukünftig könnte daher untersucht werden, wie gut ALDs im Verhältnis zu anderen Anzeigemodalitäten funktionieren.

Unser wichtigster Beitrag ist das Aufzeigen einer neuen Art mit Fahrern zu kommunizieren, ohne die Ablenkung stark zu erhöhen. Die gröSSte Einschränkung dieser Arbeit ist, dass die meisten Studien im Fahrsimulator durchgeführt wurden und es daher unklar ist, wie stark die beobachteten Effekte in einem realen Aufbau wären. Trotzdem bietet diese Arbeit einen guten Ausgangspunkt für Entwickler von Anzeigen für Assistenzsysteme. Darüber hinaus, werfen wir weitere Fragen auf und motivieren Forschungsrichtungen für zukünftige Forschungen.

[1] Ich benutze in dieser Zusammenfassung ein generisches Maskulinum für einen besseren Lesefluss. Frauen und Personen, die sich nicht als männlich oder weiblich identifizieren, sind hier explizit miteingeschlossen.

Abstract

Advanced driver assistant systems (ADAS) present several kinds of information, warnings, and alerts to drivers depending on the situation. While prior research has investigated various modalities and displays to support drivers, accidents still occur. In this thesis, we examine how we can increase driving performance by informing drivers via their peripheral vision to not distract their focus from the current driving task.

Specifically, we investigate how in-vehicle ambient light displays (ALDs) can be used to achieve this. Since ambient light is mainly perceived peripherally, it places less of a cognitive burden on the driver. Moreover, previous research has shown that ambient displays can cover a wide range of visual cues that can inform drivers unobtrusively, but also grab their attention if needed.

We explored designs for in-vehicle ambient light patterns for various use cases and derived design recommendations. Namely, we developed light patterns for assisting drivers in navigation, reverse parking, avoiding forward collisions, and changing lanes. We focused deeper on the lane change assistance to investigate the effect of ambient light on driving performance and gaze behavior. We also present future research directions, such as prototypes for easier visualization of ambient light patterns and use cases for a future in which the driver state can be assessed automatically, or automated driving makes driver assistance systems futile.

In short, our results show that ambient light displays can be designed to assist drivers in various use cases. Their main advantage is that they can present information unobtrusively but effectively. On the other hand, they can be distracting if not designed well and often did not decrease response times of drivers very much. More research has to be done to investigate the benefits and drawbacks of ambient light compared to other display modalities.

The main contribution of this work lies in a novel way to display driving-related information in a non-distracting way. Even though the results are mainly based on driving simulator studies, they provide a good starting point for developing driver assistant systems that improve driving behavior without increasing the visual distraction. In addition, this research can serve as a basis for future work in automotive ambient light displays as we open up future research directions and give design recommendations.

Contents

1 Introduction

Driving is complex and demanding. Not only does a driver need to operate the vehicle to maintain a safe lateral and longitudinal position on the street, but also to observe the traffic situation, traffic signs, and landmarks around him or her to avoid breaking laws, to keep safe distances, to optimize the get-through and to orient and navigate [End95, JLGD94]. To make driving easier, various Advanced Driver Assistance Systems (ADAS) have been introduced in the last decades. Still, some kinds of accidents stopped declining in recent years. For example, the number of accidents on German highways increased from 164,417 in 2007 to 178,861 in 2017 [Sta18b]. At the same time, the number of personal injuries and deaths on highways increased from 31,942 to 34,101 [Sta18b]. Also, the decrease in the number of killed people on German roads is becoming less. For example, 8,410 were killed in 2000, while 4,078 died in 2010, which results in an average yearly decrease of 394 deaths [Sta18b]. However, in 2017, 3,589 people died as a result of a traffic accident, which is an average decrease of only 61 deaths per year since 2010 [Sta18b].

The leading cause of accidents with personal injuries remain drivers misconducting or making errors (e.g., 87.6% on German roads in 2017 [Sta18a]). Therefore, supporting human drivers in their driving tasks has the potential to further decrease the number of injuries, deaths, or traffic accidents in general. Some assistant systems, such as adaptive cruise control (ACC), will help drivers automatically while other systems, such as navigation assistance, blind spot monitors, collision warning systems, or lane change assistants, actively try to get the driver's attention. In this work, we focus on systems that interact with the drivers.

Since the early days of driving automobiles, the primary senses for receiving necessary information for driving a car have been hearing, touch and vision. Experienced drivers may even smell the state of their car. Visual cues are widely in use when it comes to interfaces for ADAS, sometimes combined with auditory or tactile signals [Esk12]. Still, these visual cues rely on focused attention and thus may compete for a single cognitive resource which could, in turn, increase the driver's workload [Wic08].

A less investigated alternative to displays requiring focal attention is ambient displays. Mankoff et al. define these displays as "[...] aesthetically pleasing displays of information which sit on the periphery of a user's attention" [MDH+03] and present a set of heuristics to evaluate them. Matthews et al. argue that they can be used to display information with a demand for attention that is relative to its importance and define notification levels for this kind of display [MDM+04]. One of the oldest examples for an ambient display is the "Dangling String" by Natalie Jeremijenko. Weiser and Brown discussed it in 1996 as an example of "calm technology" [WB95]. They argue that placing information in the periphery enables users to process it in parallel to information in the center of the attention.

Several ambient displays are based on physical artifacts, such as the ones discussed in [MDH+03, MDM+04]. However, another way to implement an ambient display is using ambient lights. An early example is the "Hello.Wall" prototype by Prante et al. (e.g., [PRS+03, RPSvA04, SRP+05]). *Hello.Wall* is used to communicate information on a wall at different levels of privacy, depending on how close a user passes the wall. Previous research established that Ambient Light Displays (ALDs) could be used well in several domains to provide information in an unobtrusive but effective way. There are use cases for the maritime domain (e.g., [MLHB14]), aviation (e.g., [FMLB15]), and in offices (e.g., [MKP+13]). They can be worn (e.g., [FRBH16]), transportable (e.g., [OAO05]), or stationary (e.g., [KG09]). However, ALDs had not been investigated much for automotive applications when we started this research in 2013.

Based on the results of related works, we can assume that ambient light patterns can be integrated easily into the car, do not interrupt the driver from driving, and can communicate information unobtrusively. At the same time, a light pattern – e.g., a red blinking light – can be designed to disrupt in situations where the driver needs to be warned.

1.1 Research Questions and Contributions

The primary objective of this thesis is to evaluate ambient light as display modality that can be used to inform drivers in potentially safety-critical situations. We first explore designs for several driving scenarios, before we deeper analyze changing lanes on a highway. We target the lane change scenario as an example of a complex driving task in which much information is needed to avoid severe accidents. In addition to the user experience, we evaluate the impact on driving behavior and driver gaze.

The unique contribution of this work is its combination of displaying information unobtrusively through an ALD in a situation that may become safety-critical. In the following, we will present our research questions and summarize the contribution of this dissertation towards them.

1.1.1 RQ1: Which Parameters of an ALD Can Be Used for Displaying Critical Information Inside a Vehicle?

As a first step towards an in-vehicle ALD, we need to understand what kind of light patterns are well understood by drivers and do not distract from the primary task of driving. Hence, in Chapter 4, we reviewed relevant works on ALDs and present exploratory studies to learn more about the design space of in-vehicle ALDs.

This work contributes to a better understanding of the requirements for an ALD. We showed that it is possible to develop intuitive light patterns beyond indicating a status with green or red light. Further, typical concerns of drivers were outlined and possible solutions discussed. Future researchers and designers can build upon this.

1.1.2 RQ2: How Effective are In-Vehicle ALDs for Supporting the Driver?

Light patterns do not only need to be well understood but also to affect the driver behavior positively. Therefore, we tested, if drivers performed better, e.g., in terms of deciding quickly, keeping safe gaps, or avoiding errors, depending on the assistant system. We investigated several light displays and patterns for various assistant functions in Chapter 4. We focused, however, on changing lanes as a scenario to investigate this research question in Chapter 5. Changing lanes is among the most complex tasks during highway driving as it involves perception, cognition and motor skills. Further, the information that needs to be encoded has spatial and time-critical dimensions. These considerations make changing lanes an interesting scenario in which we can analyze how an ALD based ADAS affects a driver's experience, driving performance and gaze behavior. We developed design alternatives for a Lane Change Decision Aid System (LCDAS) in a participatory design process (see Section 4.5). We reiterated the design of the LCDAS and compared it to driving without assistance and driving with a blind spot notification system that is equivalent to state-of-the-art systems. Another iteration of the system incorporates a model of driver uncertainty. Our idea was to make the display most noticeable when a driver needs assistance and stay less noticeable when the driver does not need it. Also, we evaluated an ALD pattern that adapts to this model against a variant of the display that does not adapt, and against driving without assistance. In addition, we tested an adaptive ALD against an adaptive display that depends on focused attention.

We learned that drivers performed worse with the blind-spot notification system when it came to keeping a safe distance to the involved cars. While the ISO 17387 may be well-defined to avoid collisions, our results open up the question if we need to change the standard to help drivers decide before changing lanes instead of only avoiding risky decisions. The contribution of this part of the thesis lies in showing that not any implementation of an LCDAS will help drivers, while there is some evidence that a non-distracting ALD may work better than the standard solution of, e.g., blinking status indicators. Further, we gave evidence that adapting a display to the driver's state can improve the driving performance.

1.1.3 RQ3: How Do In-Vehicle ALDs Affect Gaze Behavior?

A core assumption that motivates using ALDs is that they address peripheral vision primarily. Hence, perceiving the information does not compete with cognitive resources that are needed to process information in the focused visual area. To assess how much the gaze behavior is affected by ALDs, we carried out two experiments. In the first experiment, we analyzed the gaze behavior during natural highway driving with a light pattern that does not adapt to the driver's state and compared it against driving without assistance. In the second experiment, we used a slightly modified version of the adaptive pattern in a controlled lane-change scenario and compared it against a system that needs

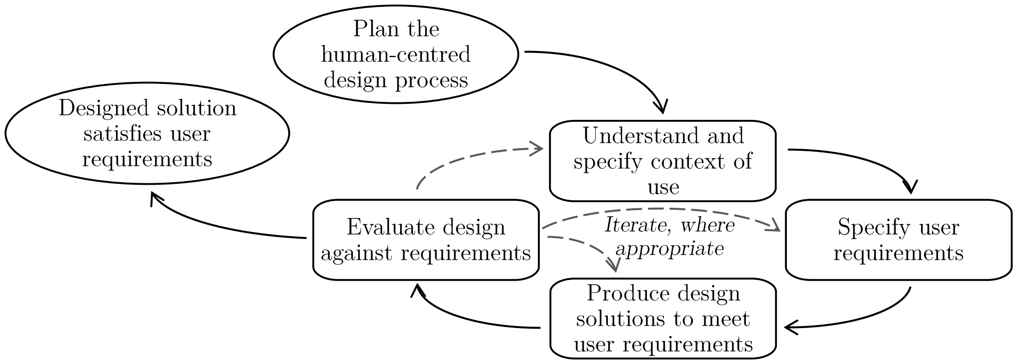


Figure 1.1: The human-centered design process according to ISO 9241-210[ISO10].

foveal attention, and driving without assistance. We observed that participants looked less often away from the center of the road, while the driving performance was similar or better than driving without assistance.

Given that this research question is the one that colleagues, reviewers, and researchers at conferences and workshops asked most often when discussing intermediate results, the answer is a major contribution of our work. While some limitations apply, our results give evidence that the common assumptions about ALDs being perceived mainly in the periphery are correct. Further, the correlation between increased driving performance and decreased focus away from the street may also indicate that the assumption about ALDs using different cognitive resources is supported. They are thus not increasing cognitive workload as much as, e.g., icons in the dashboard that need focused vision.

1.2 The Human-Centered Design Approach

In this thesis, we investigate ambient light as a modality for communicating with drivers in potentially safety-critical situations from an HCI perspective. Because this research focuses on the impact of ALDs on drivers, we decided to use a process that puts the driver needs into the center. Human-Centered Design (HCD) is such a process. ISO 9241-210[ISO10] separates this process into four phases: understanding and specifying the context of use, specifying the user requirements, producing design solutions that meet these requirements and evaluating the designs against the requirements (see Figure 1.2). Don Norman summarizes the HCD process with a stronger focus on the designer's activity within each phase [Nor13]: observe the target population, generate design ideas, produce prototypes and test them. In both cases, the process is iterative, meaning that, depending on the results, the next iteration begins with refining the context of use, the user requirements or the design. This framework helps designers focusing on human needs in every phase [ISO10].

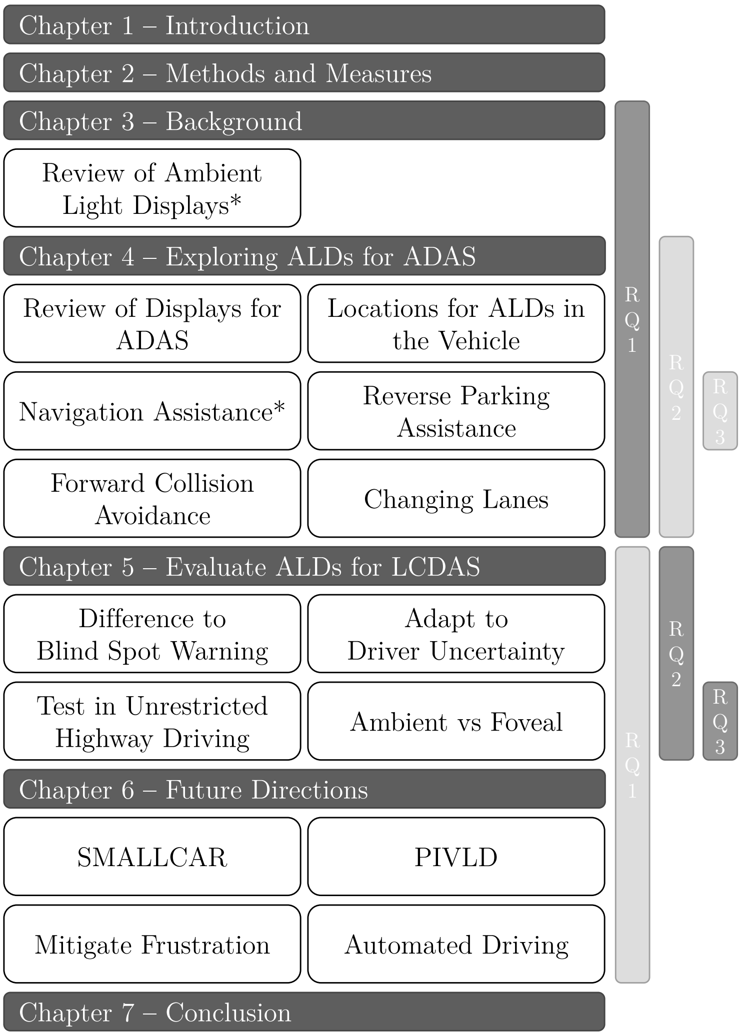


*Figure 1.2: Outline of this dissertation. The white boxes highlight the studies. Works marked with a * are only summarized in this dissertation. The gray boxes on the right highlight the contribution of each chapter towards the research questions. A dark gray box indicates parts with a high contribution to the research question, whereas a light gray box indicates small contributions.*

This research follows the HCD process with the target users being drivers of passenger cars. As the goal of this work is to answer research questions and not to develop a production ready system, most of the presented prototypes of this thesis are not refined in multiple iterations. We did one iteration per scenario to answer our first research question about well suited ALD parameters for communication. The second and third research questions are discussed based on multiple iterations for an LCDAS. We present methods and measures that we used per phase in Chapter 2.

1.3 Thesis Outline

The thesis' outline is shown in Figure 1.2. It consists of seven chapters. This chapter introduces the topic and motivates the research questions and structure of this dissertation. Chapter 2 introduces our approach and the methods used in our research, as well as a description of the conventional apparatus and measures for the conducted experiments. Chapter 3 describes theories and concepts on which this work is based and gives an overview of the general design guidelines for ambient light displays.

Chapter 4 summarizes our exploration of the design space for automotive ALDs. The focus of this chapter is on investigating RQ1. A literature survey and a study preferred locations for in-vehicle ALDs build the basis for this chapter. Four use cases are studied to explore ALDs in situations with different requirements. In Chapter 5, we discuss four experiments that measure the effect of ALDs on driver behavior when changing lanes on a highway. All of them contribute to RQ2. Two of these experiments also investigate the effect on the drivers' gaze behavior (RQ3).

Chapter 6 presents four works about ideas for future research. Two of these works introduce prototypes that could make it easier to develop and discuss light patterns for ALDs easier in early design phases. The other two works focus on future applications for ALDs. Namely, four concepts for adapting a display to mitigate frustration and a prototype for displaying the intention of an automated car to its passengers. We conclude this dissertation in Chapter 7. We reflect on the thesis and research questions, summarize design recommendations for future researches and name limitations and possible future directions if this research.

1.4 Publications

This dissertation exploits parts of previously published works that are attributable to its author. Also, we published several works during the time of researching for this dissertation that are related to this thesis, but outside its focus. In addition, several bachelor theses and student projects have been co-supervised by the author and serve as a basis for some of the results: Maximilian Hipp's work contributed to Section 4.3, Erwin Lachenmaier's work to Section 4.4, Patrick Drews' work to Section 5.3, and Jannik Spieker's work to Section 6.1. The student project of Philipp Borchers, Christian Peters, and Oliver Klemp supplied results for Section 6.2, and the project of Sebastian Warsitz and Alexander ZeySSig for Section 6.4.

The following presents three lists of publications. The first list contains works that build the basis for this dissertation. The second list consists of works that are relevant to this thesis but also contain many inputs from other authors and are therefore presented in a more summarized form that reflects the extent of the author's contribution. The third list contains works that are related to this thesis but are not discussed in detail as their content is outside its focus.

1.4.1 Important Publications for This Thesis

The following lists the publications that are an integral part of this thesis.

1. Andreas Löcken, Fei Yan, Wilko Heuten, and Susanne Boll. Investigating driver gaze behavior during lane changes using two visual cues: ambient light and focal icons. *Journal on Multimodal User Interfaces*, 13(2):119–136, Jun 2019
2. Andreas Löcken, Klas Ihme, and Anirudh Unni. Towards designing affect-aware systems for mitigating the effects of in-vehicle frustration. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, AutomotiveUI '17, pages 88–93, New York, NY, USA, 2017. ACM
3. Jannik Spieker, Andreas Löcken, Wilko Heuten, and Susanne Boll. Smallcar: A scaled model for ambient light display creation and review of in-vehicle light patterns. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, AutomotiveUI '17, pages 120–125, New York, NY, USA, 2017. ACM
4. Andreas Löcken, Shadan Sadeghian Borojeni, Heiko Müller, Thomas M. Gable, Stefano Triberti, Cyriel Diels, Christiane Glatz, Ignacio Alvarez, Lewis Chuang, and Susanne Boll. Towards adaptive ambient in-vehicle displays and interactions: Insights and design guidelines from the 2015 automotiveui dedicated workshop. In Gerrit Meixner and Christian Müller, editors, *Automotive User Interfaces: Creating Interactive Experiences in the Car*, volume 37, pages 325–348. Springer International Publishing, Cham, 2017
5. Maximilian Hipp, Andreas Löcken, Wilko Heuten, and Susanne Boll. Ambient park assist: Supporting reverse parking maneuvers with ambient light. In *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '16 Adjunct, pages 45–50, New York, NY, USA, 2016. ACM
6. Andreas Löcken, Wilko Heuten, and Susanne Boll. Autoambicar: Using ambient light to inform drivers about intentions of their automated cars. In *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '16 Adjunct, pages 57–62, New York, NY, USA, 2016. ACM
7. Andreas Löcken, Wilko Heuten, and Susanne Boll. Enlightening drivers: A survey on in-vehicle light displays. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Automotive'UI 16, pages 97–104, New York, NY, USA, 2016. ACM
8. Andreas Löcken, Wilko Heuten, and Susanne Boll. Supporting lane change decisions with ambient light. In *Proceedings of the 7th International Conference on Automo-*

tive User Interfaces and Interactive Vehicular Applications, AutomotiveUI '15, pages 204–211, New York, NY, USA, 2015. ACM

9. Andreas Löcken, Heiko Müller, Wilko Heuten, and Susanne Boll. An experiment on ambient light patterns to support lane change decisions. In *2015 IEEE Intelligent Vehicles Symposium (IV)*, pages 505–510, June 2015

10. Andreas Löcken, Heiko Müller, Wilko Heuten, and Susanne Boll. "should i stay or should i go?": Different designs to support drivers' decision making. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, NordiCHI '14, pages 1031–1034, New York, NY, USA, 2014. ACM

11. Andreas Löcken, Heiko Müller, Wilko Heuten, and Susanne Boll. Ambicar: Towards an in-vehicle ambient light display. In *Adjunct Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '13 Adjunct, pages 107–108, 2013

12. Andreas Löcken, Anirudh Unni, Heiko Müller, Jochem Rieger, Wilko Heuten, and Susanne Boll. The car that cares: Introducing an in-vehicle ambient light display to reduce cognitive load. In *Adjunct Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '13 Adjunct, pages 41–44, 10 2013

1.4.2 Co-Authored Relevant Publications

The following lists publications that are relevant to this thesis but have strong contributions from other authors. Specifically, these are the works about guidelines for ambient light displays from the *Lumicons* project, summarized in Section 3.2, and the work on navigation assistance, discussed in Section 4.2.

1. Andrii Matviienko, Andreas Löcken, Abdallah El Ali, Wilko Heuten, and Susanne Boll. Navilight: Investigating ambient light displays for turn-by-turn navigation in cars. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '16, pages 283–294, New York, NY, USA, 2016. ACM

2. Andrii Matviienko, Maria Rauschenberger, Vanessa Cobus, Janko Timmermann, Heiko Müller, Jutta Fortmann, Andreas Löcken, Christoph Trappe, Wilko Heuten, and Susanne Boll. Deriving design guidelines for ambient light systems. In *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia*, MUM '15, pages 267–277, New York, NY, USA, 2015. ACM

3. Andrii Matviienko, Maria Rauschenberger, Vanessa Cobus, Janko Timmermann, Jutta Fortmann, Andreas Löcken, Heiko Müller, Christoph Trappe, Wilko Heuten, and Susanne Boll. Towards new ambient light systems: a close look at existing en-

codings of ambient light systems. *Interaction Design and Architecture(s) Journal – IxD&A*, 26:10–24, 2015

4. Maria Rauschenberger, Andrii Matviienko, Vanessa Cobus, Janko Timmermann, Heiko Müller, Andreas Löcken, Jutta Fortmann, Christoph Trappe, Wilko Heuten, and Susanne Boll. Lumicons: Mapping light patterns to information classes. In Sarah Diefenbach, Niels Henze, and Martin Pielot, editors, *Mensch und Computer 2015 - Proceedings, Stuttgart, Germany, September 6-9, 2015*, pages 343–346, Stuttgart, Germany, 9 2015. De Gruyter Oldenbourg

1.4.3 Selected Related Publications

The following lists interesting related works that were published while researching for this dissertation but do not contribute to the focus of this dissertation.

1. Uwe Gruenefeld, Andreas Löcken, Yvonne Brueck, Susanne Boll, and Wilko Heuten. Where to look: Exploring peripheral cues for shifting attention to spatially distributed out-of-view objects. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '18, pages 221–228, New York, NY, USA, 2018. ACM
2. Tim Claudius Stratmann, Andreas Löcken, Uwe Gruenefeld, Wilko Heuten, and Susanne Boll. Exploring vibrotactile and peripheral cues for spatial attention guidance. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, PerDis '18, pages 9:1–9:8, New York, NY, USA, 2018. ACM
3. Andreas Löcken, Sarah Blum, Tim Claudius Stratmann, Uwe Gruenefeld, Wilko Heuten, Susanne Boll, and Steven van de Par. Effects of location and fade-in time of (audio-)visual cues on response times and success-rates in a dual-task experiment. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '17, pages 12:1–12:4, New York, NY, USA, 2017. ACM
4. Andreas Löcken, Hendrik Buhl, Wilko Heuten, and Susanne Boll. Tacticar: Towards supporting drivers during lane change using vibro-tactile patterns. In *Adjunct Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '15, pages 32–37, New York, NY, USA, 2015. ACM
5. Andreas Löcken, Heiko Müller, Wilko Heuten, and Susanne Boll. Exploring the design space of ambient light displays. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '14, pages 387–390, New York, NY, USA, 2014. ACM
6. Heiko Müller, Andreas Löcken, Wilko Heuten, and Susanne Boll. Sparkle: An ambient light display for dynamic off-screen points of interest. In *Proceedings of the*

8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational, NordiCHI '14, pages 51–60, New York, NY, USA, 2014. ACM

2 Methods and Measures

As described in Section 1.2, we follow the HCD process when developing our systems. This chapter provides information on methods and measures that we used in this dissertation.

2.1 Understanding the Problem

Each of our developments starts with reviewing related works. On top of that, we often used questionnaires and interviews to better understand driver attitudes. For example, we observed participants during reverse parking and interviewed them right after a few maneuvers in a semi-structured way to learn about their needs for a park distance control and how they would design an interface for such a system (see Section 4.3). Similarly, we used semi-structured interviews to receive requirements and design ideas for a forward collision warning system (see Section 4.4), and intent communication in automated driving (see Section 6.4). When developing our design tools, we interviewed experts instead of drivers (see Sections 6.1 and 6.2). We also developed an online survey to investigate where drivers would expect in-vehicle ALDs work well (see Section 4.1).

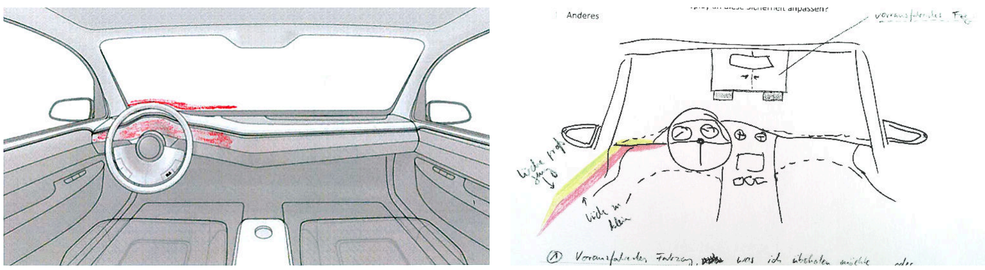
Related works do not report on this phase very often. Van Dijck and van der Heijden [vDvdH05] did an online survey to find the most suitable situation for their lateral warning system. Further, they described two light patterns and received feedback for them. Suk [Suk13] conducted two workshops to (a) map measurements to colors and rate how *interesting*, *informational* and *inspiring* such a mapping would be, and (b) map specific colors to the selected measures. Loehmann et al. [LLKB14] created *experience stories* and inferred requirements from that, before creating the first prototype.

2.2 Exploring Designs

In this phase, we create several design ideas. We usually run focus groups or workshops and let participants or experts draft design ideas.

Brainwriting

For the navigation system in Section 4.2, the LCDAS (see Section 4.5), and the scaled down model “SMALLCAR” (see Section 6.1), we did brainwriting sessions to create and discuss several design ideas. Brainwriting is a variant of the brainstorming technique that can be done with a group of well-informed participants. The first step of the process is to ensure that everyone has a good knowledge of the problem. In the second step, participants have a limited amount of time (e.g., five minutes) to write or sketch their first design ideas on a worksheet. Afterwards, this worksheet is passed to the next person. Again, everyone has a few minutes to sketch the next idea, probably, but not nec-



(a) Forward Collision Avoidance (b) Lane Change Decision Aid

Figure 2.1: Examples of sketches from participants that were produced during our studies. (a) A forward collision avoidance system is indicating a distance that is too small. (b) A lane change decision aid system. According to the sketch, safe gaps ("Lücke groSS genug") should be indicated with green color and unsafe gaps ("Lücke zu klein") in red.

essarily, inspired by the already existing ideas on the worksheet. This step is repeated for a predefined number of times, for example, until everyone receives his or her initial worksheet again. All created ideas are then discussed in the group to remove duplicates, clarify details and select the most promising designs. An instance of this method is also known as "365 method", in which six participants generate three ideas within five minutes before passing the worksheet on. Compared to brainstorming, this technique is easier to moderate and better motivates introverted people to contribute ideas.

Sketching

For the park distance control (see Section 4.3), the forward collision warning system (see Section 4.4), and the intent communication for automated driving (see Section 6.4) participants were asked to sketch their design ideas as part of an interview. Examples of these sketches are depicted in Figure 2.1.

Sketching out design ideas has the advantage that the ideas become more tangible and easier to discuss than using texts. However, some participants may be intimidated if they are asked to draw their idea. Thus, it can help to provide a basis, like the outline of a car's interior (see Figure 2.1(b)), to get them started while also providing blank sheets to not limit creativity.

2.3 Developing Prototypes

In this phase, design ideas are consolidated, and prototypes developed. Throughout this work, prototyping is used to communicate and discuss light patterns for ALDs. We usually develop low-fidelity prototypes together with drivers for this purpose.

(a) An LED strip with a simple pattern to demonstrate a possible location or a pattern of an ALD (see Section 4.1).

(b) A model of a car on a small scale to visualize and discuss light patterns in the context of the interior of a car (see Section 6.1).

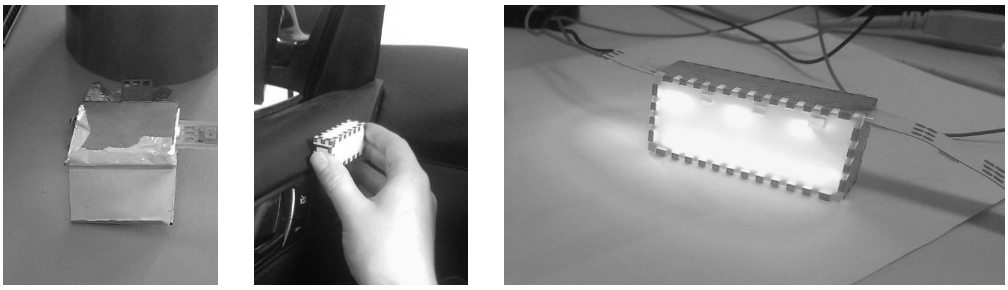
Figure 2.2: Examples of prototypes used to explore and discuss designs for ALDs and their light patterns.

Prototyping to Discuss and Select Designs

Paper prototypes and wireframes are common low-fidelity prototypes for screen-based systems. However, the behaviors of ALDs are difficult to express in this way. Therefore, the least complex prototypes are realized with LEDs or inside a simulation. To explore possible designs together with participants, we create prototypes that are easy to manipulate. For example, the LED strip shown in Figure 2.2(a) was easy to place at different places inside the vehicle. It did not need to be stable or interact with drivers because it was only needed to record a video of various light patterns at different locations which were then presented online (see Section 4.1). Another way to explore the design space is using a prototype that can have multiple light patterns or change them quickly. “SMALLCAR” is such a prototype, as shown in Figure 2.2(b), and discussed in Section 6.1. “PIVLD” follows the same motivation. Its purpose is to be able to quickly attach an ALD inside a participant’s car to demonstrate and discuss light patterns (see Section 6.2). We also used a prototype that participants could utilize to create new light patterns in the Lumicons project (see Section 3.2). Virtual Reality also offers a way to realize interactive light patterns quickly. We used it to visualize light patterns that were described in a workshop, but not for design exploration (see Section 6.2).

Prototyping to Decide for Implementation Details

Prototypes can not only be used to explore and discuss design ideas but also to test implementation details before realizing the complete concept. Figure 2.3 gives some examples for prototypes that we created to test aspects of an ALD. Most often, we needed to try different ways to fixate the light display inside a car at the correct location. We discuss the development of the ALD that was integrated into our driving simulator in more detail below.



(a) Checking how the light is scattered.

(b) Testing different ways to attach the display.

(c) One of several prototypes that were created to test the properties of the display.

Figure 2.3: Examples of prototypes that were used to explore possible ways to realize ALDs. (a) One of the prototypes used to test how the light is scattered with different materials. This one uses aluminum foil on the inside to scatter the light more and greaseproof paper to add a semi-transparent layer. (b) A prototype used in the second iteration of the ALD development. It was used to test different ways to attach the display to the interior of the car. (c) Another prototype used in the second iteration of the ALD development. We created several units like this with different parameters, like the thickness and transparency of the acrylic glass depth of the unit, or placement of the LED strip. We later withdrew this design because the individual LEDs were still too easy to see and we wanted a more uniform distribution of the light.

Early Prototypes in Related Works

Most related works do not present many prototypes apart from the one used to evaluate their systems. Meschtscherjakov et al. [MDRT15] used an early version of their prototype and ran "informal explorations" with colleagues to find suitable parameters. Trösterer et al. [TWD$^+$15] ran several "pretests" with their light display in order to check alternative designs of their light pattern.

2.4 Evaluate Solution

For most systems in this dissertation, we test the effect of the system on user experience or drivers' performance. Also in related works, it is common to combine driving experiments with questionnaires or semi-structured interviews to assess the driver experience, e.g., consisting of acceptability or usefulness of a design. In the following, we summarize methods used in this dissertation and related works.

2.4.1 User Experience

A driver needs to be able to understand a system in order to benefit from it. Further, a good user experience ensures that a driver will not turn the system off, which would make it useless. In our own and related research, systems were therefore often not only evaluated for their impact on driving performance but also on user experience or aspects of it by using standardized questionnaires or conducting interviews.

Questionnaires

We use a raw NASA Task Load Index (NASA TLX) [Har06] in the works persented in Sections 4.3 and 5.1 to measure workload. Related works often used variations of the NASA TLX and Subjective Mental Effort Questionnaire (SMEQ). Mahlke et al. [MRS+07] used a modified NASA TLX [Har06] with *visual demand* as an additional item. Trösterer et al. [TWD+15] used another multi-scale questionnaire: the Driving Activity Load Index (DALI) [Pau08]. Mahlke et al. [MRS+07], Pfromm et al. [PCB13], as well as Meschtscherjakov et al. [MDRT15] used a single scale questionnaire known as Rating Scale Mental Effort (RMSE), or SMEQ [SD09] to measure the driver's workload.

To measure the usability of our systems, we mainly used the System Usability Scale (SUS) (see Sections 4.3, 4.4, and 6.4) or User Experience Questionnaire (UEQ) (see Sections 5.3, 5.4, and 6.1) questionnaires. In related works, Loehmann et al. [LLKB14] used the User Experience Need Questionnaire (UXNQ) [KEBOM13] to assess the fulfillment of psychological needs and the Positive and Negative Affect Schedule (PANAS) [Ker92] to evaluate the positive and negative affect of drivers to their system. Meschtscherjakov et al. [MDRT15] used an adapted version of the Car Technology Acceptance Model (CTAM) [OWT+12] to quantify the usefulness, ease of use, intention to use and perceived safety. Mahlke et al. [MRS+07] used two questionnaires developed in previous works to assess acceptance and user experience. Pfromm et al. [PCB13] used a subset of a questionnaire developed by van der Laan et al. [VDLHDW97] to estimate the acceptance.

Typical questions in the custom questionnaires or interviews are asking about the intuitiveness, disruptiveness, and visibility of the light. Along with 18 bipolar scales (semantic differential), Laquai et al. [LCR11] asked if their system was appealing, intuitive and supportive. Borges et al. [BZT13] asked their participants to rate the usefulness of the system and if it behaved correctly. Pfromm et al. [PCB13] asked for the simplicity, achieved safety improvement, manageability, and distraction. Meschtscherjakov et al. [MWB15] asked for personal impressions regarding understandability, visibility, and disruptiveness of their display. Trösterer et al. [TWD+15] added an item for "distraction" to the DALI questionnaire and prepared separate questionnaires for drivers and front-seat passengers regarding distraction and features of the display. Dziennus et al. [DKS16] also checked the participant's understanding of the light patterns as well as their usability.To achieve this, they created a questionnaire with ten word-pairs, such as "avoiding" vs. "affording".

We asked for the intuitiveness, perceptibility, and disruptiveness of the light patterns in the first evaluation of our LCDAS, as described in Section 5.1. In Section 5.2, we asked the participants to rate how confident they felt with their decisions, how much they were interrupted by the light, how satisfied they were with their performance and how hard it was to make decisions.

Interviews

In the first experiment in the work of Mahlke et al. [MRS+07], participants gave *verbal reports* during the real traffic test.

Fricke et al. [FT09] interviewed participants at the end of their experiments to receive information about subjective impressions. *Semi-structured interviews* after trials are very common and were for example performed by Mahlke et al. [MRS+07], Laquai et al. [LCR11], Pfromm et al. [PCB13], Loehmann et al. [LLKB14], Meschtscherjakov et al. [MDRT15], and Trösterer et al. [TWD+15].

We also often used semi-structured interviews to get more detailed information from the driver in our experiments, as reported in Sections 4.3, 5.1, 5.2, and 6.1.

Run Dedicated Experiments

Laquai et al. [LCR11] tested the first version of their design using video-playback and the light display. Afterwards, participants rated how much they liked to use the display, how optically appealing it was, how intuitive it was and how much it supported anticipatory driving. Loehmann et al. [LLKB14] created an *experience prototype* in a static car mock-up. Furthermore, they carried out an expert study and three studies, where users were able to interact with the system and gave feedback. We ran experiments that were dedicated to finding user experience issues. This is, for example, described in Sections 4.2, 5.3, 6.1, and 6.2.

2.4.2 Driving Performance

A driving simulator study is the most common way to evaluate a light display. We conducted driving simulator studies to test almost every system within this dissertation and discuss the benefits in more detail in Section 3.3. In related works, the process is usually to implement scenarios in the driving simulator environment and invite participants to experience the display while driving [FT09, LLKB14, MDRT15]. The measurements are specific to the scenario. For example, Laquai et al. [LCR11] used a Peripheral Detection Task to increase workload and measure deceleration behavior to compare their different designs.

Pomarjanschi et al. [PDBB13], Pfromm et al. [PCB13] and Trösterer et al. [TWD+15] equipped the participants with eye-trackers to analyze gaze behavior during the driving simulation.

Only a few works that focused on ALDs evaluated their systems outside a laboratory. Meschtscherjakov et al. [MWB15] ran their experiment in a real car, but with a controlled and simplified setup. Mahlke et al. [MRS+07] tested their light pattern in a real-world scenario with instructed pedestrians. Also, our park distance control system was tested on a real parking lot, as described in Section 4.3.

2.5 Measures for User Experience, Driving Performance and Gaze

We define the measures according to the needed research questions per experiment. However, some measures are often used throughout this dissertation and are thus explained in the following.

2.5.1 Subjective Measures

Subjective measures are self-reported by the participants. We mainly measured workload and user experience within this category.

Nasa Task Load Index (TLX)

The NASA TLX, as described in [Har06], originated in aviation, but is widely used in automotive research. The scales of the questionnaire include mental, physical, and temporal demand, as well as how well subjects perceived their performance, needed effort, and frustration. The original version of the questionnaire has two steps. First, users need to pairwise weigh the scales against each other according to their perceived importance for the task. Second, users rate each scale from 0 to 100 in steps of five. However, the Raw NASA TLX is also commonly used in research [Har06] and is a variant that drops the first step.

System Usability Scale (SUS)

The SUS, as defined in [Bro14], is a questionnaire that is widely used to assess the usability of an interactive system quickly. It consists of ten items to which participants agree or disagree to some extent. The aggregated score ranges from 0 to 100. A score of above 68 related to a system is considered more usable than the average.

User Experience Questionnaire (UEQ)

The UEQ [LHS08] is a more recent questionnaire with 26 scales, available in several languages. Each scale is a pair of contrasting attributes, like "boring" and "exciting". Users can select which attribute describes the system better on a scale from -3 (e.g., "boring") to +3 (e.g., "exciting"), including 0. For the analysis, the scales are aggregated into six aspects: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty.

2.5.2 Objective Measures

We can observe all object positions and speeds in the driving simulator setup and thus can derive measures that indicate safe driving behavior, such as overall speed of the own car, distances to the surrounding cars, but also decision times. These measures are frequently used in our studies and described below.

Distance

Within the scope of this thesis, the *distance* between two vehicles is measured from the front most part of the trailing vehicle to the back most part of the lead vehicle. It is in line with the definition of *distance gap* in SAE J2944 [SAE15].

Gap Size

Throughout this dissertation, we use the term *gap size* or *gap* to refer to the longitudinal distance between to vehicles. Our definitions follow the definition for *time gap* in SAE J2944: "Time interval, usually measured in seconds, for a following vehicle's leading surface to reach the current location of the trailing surface of a vehicle ahead." [SAE15].

The gap size gives a reasonable estimate of the safety of a gap. For example, a gap of two seconds to the leading vehicle is considered safe as a rule of thumb in many countries. However, the time gap does not take the velocity of the other vehicle into account. For example, a time gap of one second to a leading vehicle that drives faster is arguably safer than a time gap of two seconds towards a wall.

Time To Collision (TTC)

We use *time to collision* frequently in this research. Within the scope of this thesis, it refers to the time a vehicle needs to collide with another object if the current velocities of both stay constant. SAE J2944 distinguishes between two kinds of Time-To-Collision (TTC): the one that includes the current acceleration, *Option A*, and the one that does not, *Option B* [SAE15]. Because our scenarios did not include big changes in acceleration or declaration, we decided to use the faster to calculate Option B that is based on constant speed and heading angle. If not stated otherwise, we use TTC in situations where cars are either on the same or adjacent lanes. Thus, we simplified the definition for TTC to

$$TTC = d/(v_{trailing} - v_{leading}),$$

with d as the distance and v as velocity where $(v_{trailing} - v_{leading})$ must be positive.

TTC gives an estimate of the dangerousness of the current distance. However, the actual distance also needs to be considered because dangerously small distances would be assumed safe as long as the leading vehicle is faster.

Glance Duration, Location Probability, and Frequency

The standards ISO 15007 [ISO14] and SAE J2396 [SAE00] define terms and give guidelines for measuring driver visual behavior experiments with video-based techniques. SAE J2396 proposes four definitions for glances but recommends to use the one also defined in ISO 15007. We follow this definition and define a glance as the first transition towards an Area of Interest (AOI) and all subsequent fixations within the same AOI until the focus transits to another AOI. Also, following the standards, glances of less than 200ms were added to the forward AOI.

We also apply the standards to the measures. Therefore, glance duration is defined as the time from the start of the eye movement towards an AOI until the last fixation ends and measured in seconds. Glance location probability is the probability that the eye is fixated on an AOI per maneuver. Glance frequency is the number of glances towards an AOI per second.

The Used Eye Tracker and Software In our experiments, we measure glance behavior with head-worn Dikablis eye tracker glasses from Ergoneers[1]. The pupil-camera resolution is 384x288 pixels, and the field-camera resolution is 768x576 pixels. Both cameras record with 25fps.

In Section 4.2, we used the standard software, provided by Ergoneers to analyze gaze behavior. However, the pupil recognition rate using the provided software was below 75% for two people in the experiment described in Section 5.3 and six people in Section 5.4. Hence, we decided to implement a custom pupil recognition application using the ExCuSe and ElSe algorithms by Fuhl et al. [FKS+15, FSKK16] for the analysis of these experiments. We ran three analyses in parallel for each frame by using ExCuSe, ElSe with a morphologic split, and ElSe with an algorithmic split. Each algorithm ran multiple times with different filters, e.g., Gaussian smoothing at different levels or histogram normalization. A pupil location is considered valid if all algorithms proposed the same location within a maximum error level of five pixels. This error level was found exploratory: it is big enough to converge quickly but small enough to not cause issues in the later categorization into AOIs.

[1] http://www.ergoneers.com

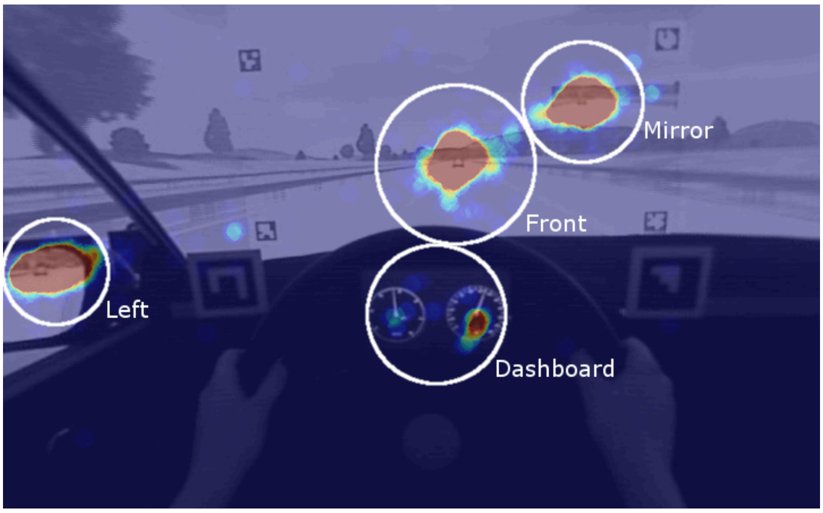


Figure 2.4: Example heatmap with AOI locations derived from all pupil-locations on the keyframe for the center area during one condition in the experiment discussed in Section 5.4.

We repeated the analysis three times. In the first run, we considered the whole eye camera frame. In the second run, we searched for unassigned pupil locations within the area where all other pupil positions were found. In the third run, we searched within the area spanned by the area of the previously identified pupil location and the next identified pupil position. After the analysis, we set locations that were outside of the median +/- 2.5 IQR location area to "unassigned" in order to reduce the number of false positives.

The pupil locations in the video are automatically mapped to locations on the field video. The calibration is based on at least six pairs of pupil locations that are manually mapped to the corresponding locations in the field video. Three frames of the field video were selected as keyframes for the left, center and right areas per video. In this way, we were able to map the pupil positions to the keyframes using perspective transformations. The pupil positions per keyframe were then manually aggregated into areas of interest (AOIs). In the context of our experiments, we defined five areas of interest: *left mirror*, *right mirror*, *rear-view mirror*, *dashboard*, and the *road ahead*. Figure 2.4 shows an example heatmap for one video and the locations of the AOIs.

We use the IQR rule to identify outliers and to decide for a threshold for an acceptable minimum percentage of categorized frames ($Mdn - 1.5 \cdot IQR$). If the mean ratio of assigned pupil positions is below this threshold for at least one condition, the participant's eye gaze data are removed from the gaze analysis. This filter only affected the results of Section 5.4 due to (a) moving the glasses during the experiment, (b) very big pupils and (c) bad positioning of the pupil camera resulting in many reflections on the eye's surface. Also, the software stopped recording halfway through the experiment once.

3 Background

The interaction between humans and machines largely depends on human performance. The performance of a human is limited by factors like age, state of the driver, attitudes towards the machine, or understanding of the system. It also depends on how well the interaction was realized. Therefore, this chapter summarizes relevant human factors and theories that are fundamental to the design of ALDs. In addition, we give an overview of the design guidelines for ALDs that are not specific to the automotive domain. Although not all studies took place inside the driving simulator, we present it, its limitations and the development of the embedded light displays at the end of this chapter.

3.1 Human Perception, Information Processing, and Decision Making

In order to make good driving decisions, drivers need to perceive and process information. The following summarizes human vision, how the perceived information is processed and which other factors may influence the decision making.

3.1.1 Visual Perception

We can manipulate the color and brightness of light to define patterns for ALDs, More complex patterns may have a spatial and a temporal dimension, meaning that we can control where the light is activated and add, e.g., blinking, or fading with different frequencies. To anticipate the effect of manipulation of light parameters, we need to introduce some basics about human vision.

Physiology

In short, the light goes through the lens into the eye and hits the retina. There, different kinds of photoreceptor cells trigger electrical signals that are collected by ganglion cells and transferred to the brain via optical nerves. The different kinds of photoreceptors are not evenly distributed throughout the retina (see Figure 3.1) [Wan95, Dow07]. In the fovea, at the center of the eye, are only cone cells. These are the three different kinds of photoreceptor cells that enable humans to distinguish colors. These cells allow for high visual acuity. Their density is highest in the center and decreases rapidly towards the periphery, to level off after more than 12° away from the fovea. Rod cells – the fourth kind of human photoreceptor cells – are missing in the fovea, but their frequency increases rapidly to peak at about 10° to 20° and then decrease slowly. Rod cells are not used for color perception but are very sensitive to light [Wan95]. The density of photoreceptors decreases towards the periphery, and the number of cells that are connected to a ganglion cell is much higher in the periphery. Also, the ratio of the visual cortex in the brain that is dedicated to analyzing signals from the periphery is smaller than that for foveal vision.

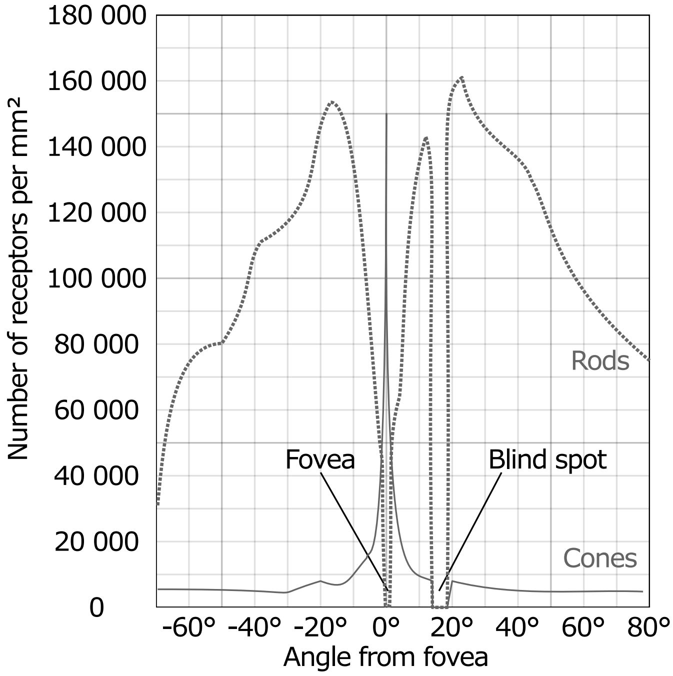


Figure 3.1: Density of the rod (dotted red line) and cone (solid blue line) photoreceptor cells of a left human eye along a line through the fovea and the blind spot based on [Wan95]. By Cmglee (`https://commons.wikimedia.org/wiki/File:Human_photoreceptor_distribution.svg`), Human photoreceptor distribution, `https://creativecommons.org/licenses/by-sa/3.0/legalcode`.

For example, the central 24°-30° are mapped to 80% of the visual field [Hor91]. Due to these reasons, color vision and visual acuity decline towards the periphery.

Foveal and Peripheral Vision

There are several ways to distinguish foveal, peripheral vision, and the levels in between. Within the scope of this thesis, we distinguish between foveal and peripheral vision, separated at 30° away from the fovea, unless stated otherwise. With a threshold of about 30°, foveal vision is characterized by a decreasing but relatively high visual acuity and strong color perception. Peripheral vision, on the other hand, has the following relevant properties: it has poor to no color perception but is good at perceiving dim light sources and flickering. In driving, foveal vision is used to observe the environment, displays, and signs inside and outside the car. Peripheral vision, on the other hand, is used for spatial orientation, often together with other senses [LSP84].

Considering these characteristics, signals that address peripheral vision must not rely on color or high visual acuity. Brightness and movement may be good parameters to show information in the periphery.

Vision Deficiencies

The most relevant vision deficiencies for this work are decreased vision due to refractive errors or diseases (about 20% of the world's population from presbyopia alone [FTR+18]) and color-blindness (8% of the male population with Northern European descent [DW11]). However, both kinds of deficiencies affect foveal vision more than peripheral vision.

While these vision deficiencies need to be considered, bad acuity or bad focusing are not the only factors causing drivers to fail to detect or recognize hazards, as summarized, e.g., by Hole [Hol07]. For example, during nighttime driving, drivers are likely to get blinded from other headlights and need about ten seconds until the visual system adapted [Hol07]. Another major factor is "looked but failed to see" which describes situations in which drivers should be able to detect objects based on the physiological factors but did not perceive them [Hol07]. This problem lies in the way information is processed by the cognitive system.

3.1.2 Information Processing and Decision Making

The perception of light is not only affected by the visual system, but also by a human's capability to process the information. Also, the quality of the drivers' decisions depends on their ability to assess current and future driving situations. The following summarizes models on how drivers process necessary information.

Hierarchy of Driving Tasks

Literature separates driving tasks into a hierarchy with three levels: long-term planning, called "Strategic Level", decision-making, called "Maneuvering Level", and (re-) actions, called "Control Level" [Mic86]. At a strategic level, drivers may, e.g., decide for a route or plan when to start a trip. At the maneuvering level, drivers decide for upcoming maneuvers, e.g., when to initiate overtaking. At the control level, drivers control the car, e.g., by braking.

The most interesting level for this dissertation is the maneuvering level. The strategic level does usually not include safety-critical decisions. Also, other modalities, such as screens, can provide information with more relevant details for tasks at this level. In situations that need quick reactions, such as a call for immediate braking, drivers need to be assisted with cues that trigger fast responses, such as multimodal signals [PBP14]. Therefore, ALDs may not be the strongest kind of displays at the control level, although applications exist, such as "ChaseLights" for maintaining speed [MDRT15].

Our goal is to support drivers at the maneuvering level. At this level, decisions are made within seconds, and bad decisions may thus have an impact on safety. Further, assistance systems for this level communicate more information than warnings and must not interfere with tasks at the control level. Therefore, the signals need to be understood fast and intuitively, to not distract from other tasks, and to not annoy enough that drivers would turn them off.

Situational Awareness

The perception and assessment of the current situation are most important for taking the right decision at the maneuvering level. In other words, drivers need to have good situational awareness. Endsley proposed a model in which building situation awareness consists of three levels and is affected by several factors [End95]. The three levels are "Perception" (Level 1), "Comprehension" (Level 2) and "Projection" (Level 3). Perception consists of perceiving relevant elements in the environment. Tasks at this level include, e.g., object recognition or cue detection. Comprehension consists of understanding the situation. Tasks at this level include, e.g., connecting the perceived information (Level 1) to a broader picture. Projection consists of predicting future actions of the elements in the environment. The main task is projecting the future behavior of elements based on the assessment of the current situation (Level 2). Factors that impact the situational awareness are the complexity of the environment and the task, the driver's state, and other individual factors such as the driver's goals, abilities, or experience. Among others, the driver's state refers in this context to his or her mental workload, stress level, or sleepiness.

In this research, we aim to support the drivers' situation awareness at the first level, by providing additional information with appropriate saliency. In several prototypes, we also encode the meaning of the information, e.g., if a gap can be considered safe, to support the second level of situation awareness. Apart from the intent communication prototype (see Section 6.4), our designs do not explicitly support the third level. However, many of our patterns use continuously changing patterns which may make it easier to interpolate future states of the patterns and thus the information that is encoded.

Multiple Resource Theory

One of the factors that influence driving performance is how efficient drivers process relevant information via different sensory channels. For example, road signs or speedometer address vision, the motor sound or navigation device address hearing and the angle of the steering wheel or accelerator pedal address touch. Wickens' Multiple Resource Theory, as summarized by Wickens in [Wic08], is a model that describes the separate cognitive resources that are needed for information processing. According to this model, information is perceived via separate modalities, such as the auditory and visual modality. The information is then processed via separate resources and also the response claims separate resources, such as the speech vs. manual control. The model suggests that parallel tasks that require the same resources are more likely to result in failures to respond appropriately than tasks that require distinct ones.

A key motivation for using ALDs to support drivers is that peripheral vision and foveal vision are separate modalities [LSP84, Wic08]. While many current infotainment systems and driving itself demand foveal visual attention, ALDs primarily address peripheral vision. Using another modality could, therefore, make it easier to perceive the added information from our ALD in parallel without increasing the mental workload if there are no added resource conflicts at the processing stage.

Driver States

To the best of our knowledge, there exists no universally accepted definition of what contributes to the state of a driver. In the context of this dissertation, we aggregate individual factors that affect situation awareness and thus driving performance differently over time into the concept of "driver state".

Coughlin et al., for example, summarize related concepts into "arousal" and argue that it can range from fatigued to overloaded with the optimal level in between [CRM11]. This stresses that it is not only important to avoid expecting too much of drivers, but also to keep them attentive. From this perspective, the worst design would alert an already overloaded driver or calm a fatigued one.

Another related concept that is influenced by several factors is the mental workload. Wickens describes mental workload as the ratio of cognitive demands per available cognitive resources [Wic08]. Similarly, mental demand, or mental effort, is defined as a counterpart to physical effort and used in workload questionnaires, like the NASA TLX [HS88]. The mental workload in driving can be self-assessed, derived from driving performance, or derived from physiological measures.

Related to arousal is the concept of driver distraction. While alertness in this context refers to the overall mental readiness of the driver to react, distraction relates to how much the driver is engaged into tasks that are not essential for driving. A bilateral task force with US-American and European experts defined driver distraction as "the diversion of attention from activities critical for safe driving to a competing activity"[US-10]. Being distracted, e.g., by using a mobile phone, results in more crashes, and impacts the flow of traffic negatively. This effect was for example shown by Stavrinos et al. for young drivers [SJG+13], but also to a lesser extent for more experienced drivers by, e.g., Klauer et al. [KGSM+14] or Kass et al. [KCS07]. Within the scope of this dissertation, we did not investigate how distraction affects driving. However, related works already gave evidence that ALDs may get the attention of a distracted driver efficiently. For example, Sadeghian Borojeni et al. used ALDs to get the attention of a distracted driver to display a take-over request [SBCHB16] or help them to resume their task after an interruption [SBAHB16].

Another aspect of a driver state that affects the driving performance is uncertainty. Yan et al. define a driver's uncertainty as their "difficulty in a given lane change situation to decide whether to overtake or to wait"[YEBL16]. However, this definition can be extended to include general situations in which it is difficult for a driver to decide which action to take. While the uncertainty is affected by a driver's experience, trust in his or her skills, and trust into the capabilities of the car, it is more dynamic and may change quickly, depending on the driving context. Yan et al. showed that adapting a display to their model of a driver's uncertainty can reduce reaction times and increase trust into the acceptance of their proposed system [YELB17]. We discuss a pattern that adapts to this aspect of driver state in Sections 5.2 and 5.4. We chose driver uncertainty because it is well defined, and a usable model was readily available.

Another aspect of the driver state is the driver's emotion. For example, Pêcher et al. [PLC09] found that listening to happy, sad and neutral music while driving changed the average speed and lateral control significantly: driving with happy music led to a slower speed and less control. Frustrated drivers, on the other hand, are more likely to show aggressive behaviors towards other traffic participants [Mar97], but also to experience stress [Edw16]. Consequently, emotions with known negative effects need to be prevented. In Section 6.3, we present ideas for light patterns that adapt to driver frustration. However, as adapting to emotions is not in the focus of this dissertation and reliable real-time emotion detection in the car is a research field on its own, we decided not to investigate further.

3.2 Ambient Light Displays

The works of Matthews et al. [MDM+04] and Mankoff et al. [MDH+03] define ambient displays. Mankoff et al. show that ambient displays can be designed to display important non-critical information [MDH+03]. While being ambient, they can cover a broad range of saliency levels [MDM+04, PS06]. To discuss ambient displays and come to a definition for the automotive domain, we organized a dedicated workshop at the AutomotiveUI conference in 2015 [LSBM+15]. About 40 participants from different academic disciplines and industrial areas participated. Amongst others, we were able to agree on the following definitions:

> 1. *Any modality of output that does NOT require immediate action and can change its state to communicate information.*
> 2. *Information in any modality that notifies the users to communicate with them, but cannot be manipulated.*
>
> [LSM+17]

However, the previous guidelines and definitions do not focus on ambient displays that utilize light. Therefore, we developed definitions and guidelines for ambient light patterns within the "Lumicons" project. As the author of this dissertation was only one of several contributors to this project, the results of this project are summarized below appropriately.

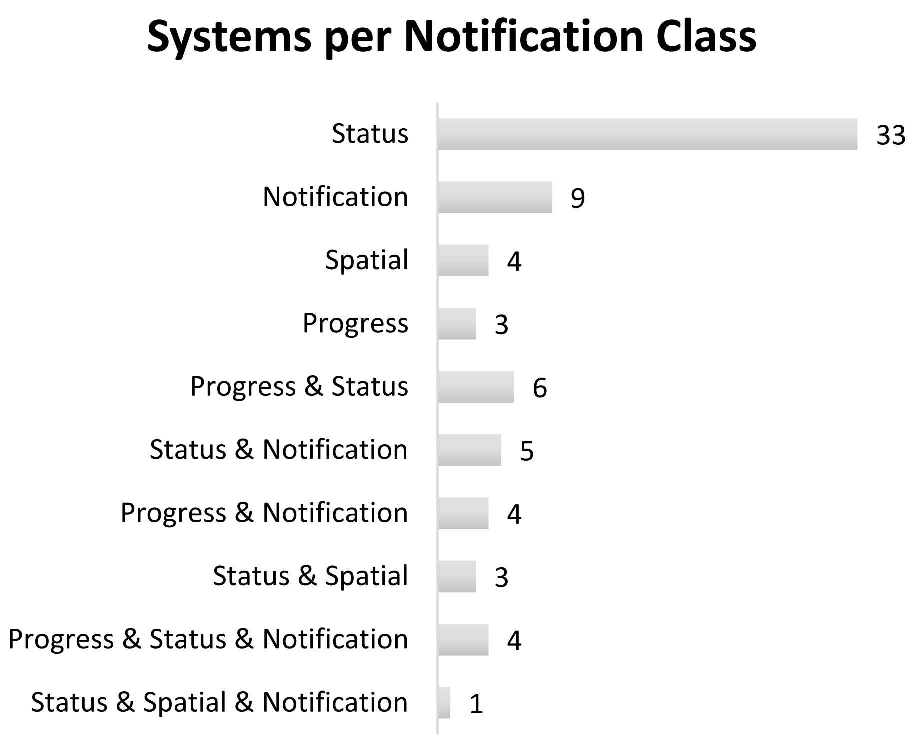


Figure 3.2: Number of categorized systems per combination of information classes.

3.2.1 Existing Encodings of ALDs

An essential part of the "Lumicons" project was the analysis of 72 systems from 66 papers that use ambient light. The goal was to derive common information classes and to identify how they are usually encoded. We contributed to this joint work and summarize relevant parts for this dissertation here. More details are published in [MRC⁺15a].

Our definition of ALDs, here called "ambient light systems", is as follows:

> *An ambient light system (ALS) is a system positioned in the periphery of a person's attention that conveys information using light encodings in a non-distracting way most of the time.*
> [MRC⁺15a]

3.2.1.1 Information Classes

The systems can be categorized into (a combination of) the following classes:

- **Progress** shows a relative indication of goal achievement by monotonously increasing or decreasing values.

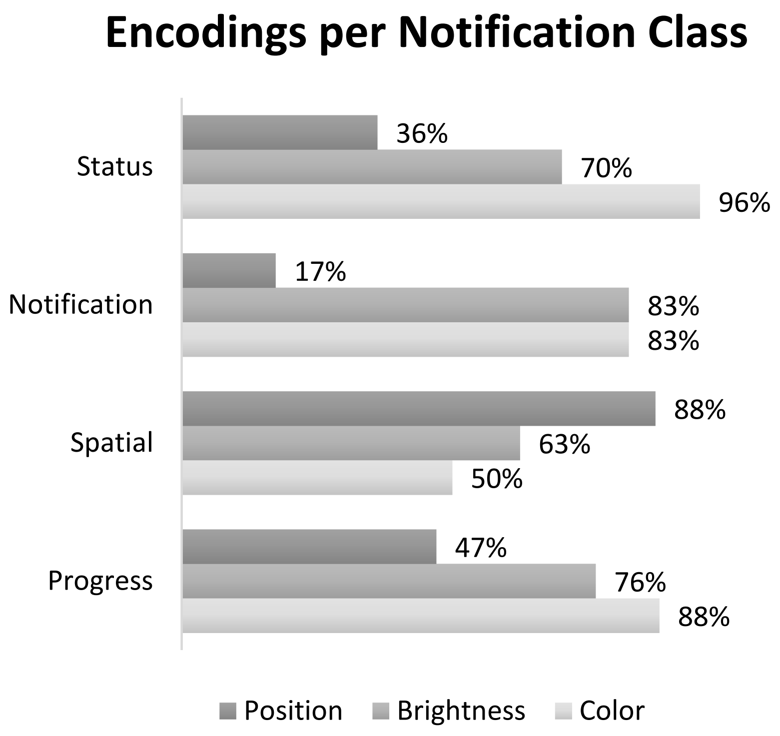


Figure 3.3: Ratio of used encoding per information class. Systems count towards each encoding when they use more than one. Also, systems that encode more than one information class count towards each information class.

- **Status** shows the absolute current value with a possible change of tendency and no indication of goal reachability.
- **Spatial** shows a direction to a point-of-interest.
- **Notification** shows information that grabs the user's attention.

As shown in Figure 3.2, ALDs primarily encode a *Status* information (33/72). Nine systems give a *Notification*, four present *Spatial* information, and three visualize *Progress*. 23 of the 72 systems present multiple information at once.

3.2.1.2 Common Encodings

Figure 3.3 gives an overview of the observed encodings per notification class. Color is the most prominent encoding. 20 systems use color alone, 24 in combination with brightness, nine in combination with brightness and the position, and six in combination with the position. Brightness alone is only used by four systems, but seven times in combination with position. The light cue's position alone is only used twice and both times for spatial information.

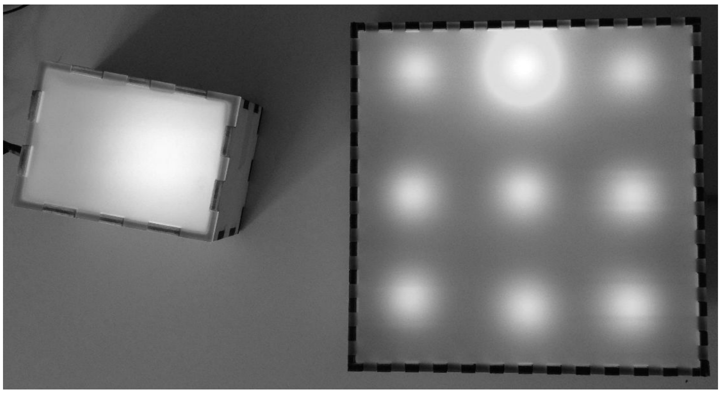


Figure 3.4: The Arduino prototypes used in the first experiment. Left: the single light display. It uses twelve RGB LEDs to show different colors and brightness levels. Right: the spatial data display. It uses nine RGB LEDs in a 3x3 LED matrix with only one color. This display can activate LEDs at different locations to convey spatial information. An Android application controls both displays via Bluetooth.

Progress information is mainly realized using color in combination with another parameter. Status information mostly uses color alone or in combination with another encoding. Spatial information is mainly encoded using the light cue's position alone or in combination with another parameter. Notification information mainly uses brightness or color or a combination of both.

3.2.1.3 Common Contexts of Use

Home and office environments are the most common contexts of the analyzed ambient light systems (34 systems each). Twelve systems are designed for everyday activities. Five systems are used for navigation and four in an automotive context. Eight systems are mainly used in other environments.

3.2.2 Deriving Design Guidelines for ALDs

Another goal of the "Lumicons" project was deriving design guidelines for systems that use ambient light. Parts of this joint research are relevant for this dissertation and are thus summarized in this section. Further details were published in [RMC+15, MRC+15b].

Following up on the previous analysis, two experiments were conducted to derive design guidelines. In the first experiment, we defined at least two everyday scenarios per information class and let participants design light patterns. In the second experiment, we presented these patterns to other people and tested if they were understood intuitively. We present the results of both experiments in [MRC+15b].

Which Light Patterns do Participants Design?

15 people (7 female) participated in the first experiment. We presented 11 scenarios, at least two per information class, such as "Imagine you are going for a walk. How could light inform you about the current distance to your home?". Each participant selects corresponding parameters for the prototype shown in Figure 3.4. To define a pattern, participants first need to choose one of 13 colors (including white) at one of three brightness levels (black/off, medium, bright). Next, they need to select a second color in the same way and decide how the first color should transit into the second (linear gradient or distinct change of color and brightness). This step can be repeated several times to create complex patterns.

Do Participants Understand our Light Patterns?

Twelve light patterns, at least two per information class, were derived from the first experiment. 30 participants rated how well each light pattern encodes each of the eleven scenarios and commented on their decision by thinking aloud.

Guidelines

Based on both experiments, nine design guidelines for ALDs were derived [MRC+15b]:

GL1: When red and green colors are used in combination, red is perceived as negative and green as positive, but not when they are used separately.

GL2: The middle color of a fade is not crucial, but the colors of initial and end states are.

GL3: For Progress, a linear color fade is the most suitable, whereas for Status it is stepwise.

GL4: Usage of traffic light colors is the most frequently suggested light combination for assessment of everyday situations.

GL5: Color is unimportant for spatial information encoding.

GL6: 4-position light pattern is the most suitable for turn-by-turn and 8-position for compass information encoding.

GL7: Red blinking light is the most suitable pattern for urgent notification encoding.

GL8: Color is not important for non-urgent notification encoding.

GL9: Elderly persons perceive colored blinking light as an urgent notification

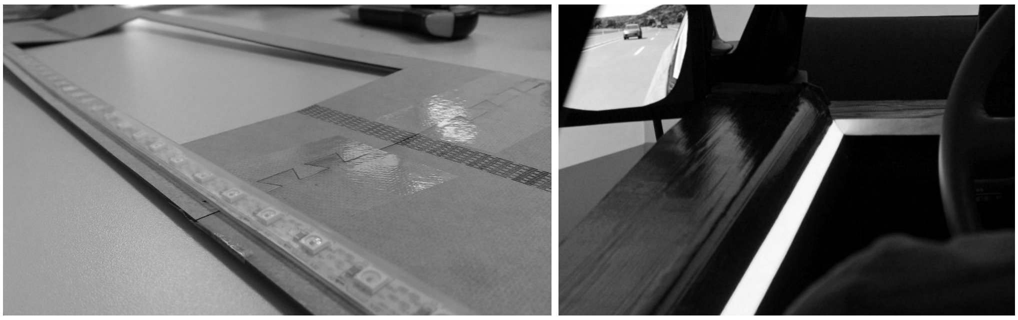


Figure 3.5: Front part of the first ALD during development (left) and integrated (right). The material was bent over to form a triangular profile, similar to the one in Figure 2.3(a). The LEDs then beam mainly at the aluminum foil and thus only indirectly and through a sheet of greaseproof paper at the driver.

3.3 The Driving Simulator Used in Our Studies

In our studies, we use a fixed-based driving simulator with a field of vision of 150° utilizing three projectors. Three Lexium Schneider CAN bus servo drives (LXM05A) apply force feedback and vibration signals with adjustable amplitude and frequency on the steering wheel as well as accelerator and brake pedal. The SILAB[1] software generates the 3D simulation environment and simulates the traffic scenarios. The room's ambient brightness and temperature can be controlled to guarantee the same conditions for all participants in the experiments. The integrated ALDs, as well as the limitations of driving simulator studies, are described below.

3.3.1 First Iteration of the Integrated Light Display

This ALD was used in the experiments presented in Sections 4.5 and 5.1. As we will discuss later (see Chapter 4), one of the essential requirements for an ALD is that it must not blind drivers. Also, it needs to be able to run different light patterns because we want to use it for several experiments. Figure 3.5 shows the flat corpus for the LED strip. We cut the corpus out of a sheet of Kraftplex[2], a bendable material made of wood. We added a bending pattern to make it easy to create a triangular profile. Inside the corpus are Adafruit NeoPixel RGB LEDs[3], which are based on WS2812B 4-pin chips, with a resolution of 60 LEDs per meter. To avoid blinding drivers, we added greaseproof paper as a semi-transparent foil in front of the LED-stripe at a distance of 2cm. This implementation scatters the light and smooths transitions. We designed the display as an add-on for the driving simulator platform, so we can easily replace it with a refined version.

[1] http://www.wivw.de/en/silab
[2] https://www.kraftplex.com/en/
[3] http://www.adafruit.com/products/1138

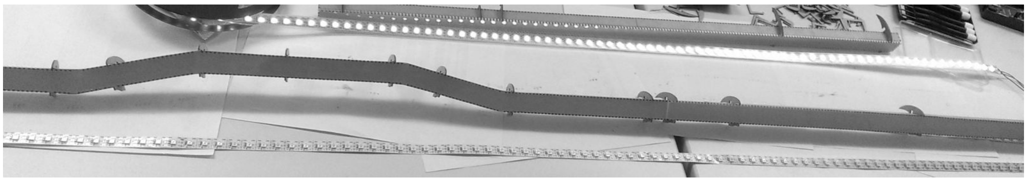


Figure 3.6: The second iteration of the light pattern during development. The corpus for the LEDs is more robust and easier to maintain than the one of the first display. However, the mounting is not robust enough to be used reliably.

To control the display, we use an Arduino Mega 2560 micro-controller[4]. Light patterns can be implemented as state machines on the Arduino or controlled via a PC. Using state machines enables us to have high update rates since only updates need to be sent via the USB connection. However, it is sometimes easier to control each LED in real time via the PC for rapid prototyping.

During a driving simulation, the simulator sends information about the own vehicle and other road participants via Ethernet to a dedicated PC. There, the data are received by a dedicated Java application. After processing, the application sends commands via a serial connection to the Arduino, which updates the LEDs accordingly.

3.3.2 Second Iteration of the Integrated Light Display

During the first driving simulator experiments, we learned that the first implementation was cheap and quick to build, but neither robust enough nor very easy to maintain. Thus, the approach for the second iteration was to keep the implementation but to update the corpus for the LEDs. Figure 3.6 shows the display during development. This display consists of two components: The corpus, a long version of the prototype shown in Figure 2.3(c), with the LEDs inside and a layer of frosted acrylic glass in front, and mounting brackets. In contrast to the first iteration, the corpus is not made from one piece, but from multiple pieces creating a long box. The acrylic glass makes the prototype more robust. Furthermore, this design needs less space than the previous one. Also, the display is easy to dismantle to replace broken LEDs.

In contrast to the depiction in Figure 3.6, the mounting brackets are placed at every 1.4cm. Because of the changing profile of the doors and the front of the interior, where the display should be mounted, several variations of the mounting brackets needed to be designed. However, these brackets were not stable enough to last multiple experiments. Instead of further refining this design, we decided to create a third version of this display.

[4] `http://arduino.cc/en/Main/ArduinoBoardMega2560`

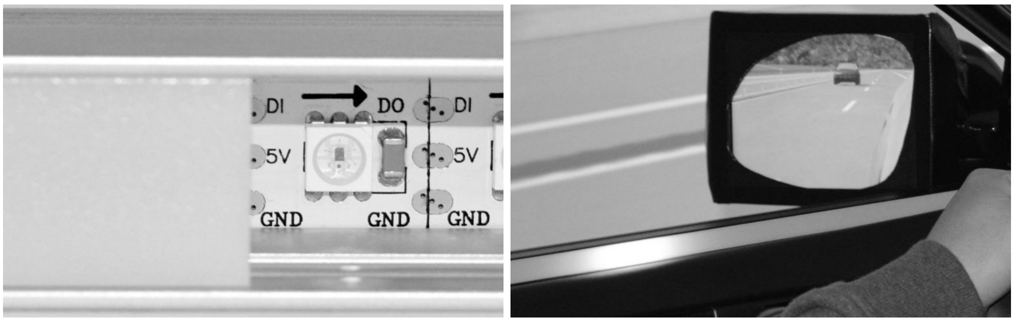


Figure 3.7: Components of the third display. An LED stripe with 72 LEDs per meter is embedded into an aluminum profile and covered by a milky diffuser.

3.3.3 Third Iteration of the Integrated Light Display

The first version of our integrated ALD was not maintainable enough, while the second version was too easy to break. Hence, we developed a third version. We used it in the experiments described in Sections 4.4, 5.2, 5.3, 5.4, and 6.4. Again, the goal was to create a robust display that is easy to maintain. As shown in Figure 3.7, this version is based on an aluminum profile with a milky diffuser, which is already commercially available. The mounts were realized using "Gorilla Plastic"[5], which is a modeling material that is only formable at temperatures above 65°C. Using this material enabled us to create a form that fits the aluminum profile seamlessly between A- and B-pillar, as shown in Figure 3.7.

We used RGB LEDs to implement the display. They are based on WS2812 3-pin chips and fixated on a strip with a resolution of 72 LEDs per meter[6]. The left part of the light display is located below the left window with a length of 80cm from A-pillar to B-pillar and thus consists of 57 LEDs. Analogously, the right part is located below the right window and the front part between the A-pillars with a width of 108 LEDs.

Again, we use an Arduino Mega 2560 micro-controller[7] to control the display. In most experiments, a dedicated Java application on a separate PC sends updates to the Arduino, which updates the LEDs accordingly. However, it is possible to connect the Arduino directly to one of the driving simulator PCs and receive information via the serial connection. Connecting the Arduino directly to the simulator removes the need for a dedicated PC and makes the setup easier. However, the light patterns then need to be entirely implemented on the Arduino.

[5] http://www.gorilla-plastic.de/
[6] http://www.watterott.com/de/WS2812-RGB-LED-Stripe-72
[7] http://arduino.cc/en/Main/ArduinoBoardMega2560

3.3.4 Limitations

There are three main reasons to use a driving simulator instead of testing the interfaces in the field. First, many of our scenarios take place at high velocities. For example, the own car drives more than 100km/h in the scenarios “changing lanes” and “maintaining a safe forward gap”. Therefore, we would put our participants at an unacceptable risk in case the tested displays do not affect them as hypothesized. Second, we can control the ambient lighting conditions in the lab and thus keep them constant across trials. Third, we do not need to rely on real-world sensors to gather and display information about the environment. While we cannot test for sensor noise or errors in this way, it makes it much easier to develop different display concepts quickly. Similarly, it is also easier to implement assistance systems if future states of the simulation are known.

While driving simulator studies are common when researching automotive user interfaces (e.g., [FT09, LCR11, PDBB13, PCB13, LLKB14, TWD+15, MDRT15]), their results are not necessarily as valid as the ones from field experiments. Kaptein et al., for example, surveyed validation studies and pointed to some limitations of fixed-base driving simulators [KTv96]. According to the authors, behavioral effects are relatively valid, but not absolutely. For our experiments, this means that effects, for example, on the chosen velocities or gaps, are also likely to be observed in the same direction in field experiments, but not likely to have the same absolute difference. Wang et al. looked into the validity of driving simulator studies when investigating in-vehicle interfaces [WMR+10]. Their results give evidence that a fixed-base, medium fidelity driving simulator, such as the one used in our experiments, is suitable for observing effects with relative validity. In their experiment, the gaze analysis revealed consistent results in the simulator and the field [WMR+10].

Considering the results mentioned above, we argue that our results are at least relatively valid. Therefore, the observed directions of our effects are likely to be similar in the real world, but the size of the effect would need to be validated with field experiments. This dissertation is exploring how ALDs can be used to affect driving performance positively. Although the impact in real driving conditions would be interesting, the benefits of using a driving simulator studies outweigh the benefit of obtaining absolute validity at this stage.

3.4 Summary

This chapter gives an overview of the fundamentals of this thesis. We summarize the relevant aspects for visual perception as the works in this thesis rely much on peripheral vision. We further present theories on information processing and decision making that build the basis for our hypotheses, e.g., that addressing peripheral vision may reduce driver’s mental workload. Also, we present basic guidelines for developing ALDs and discuss the characteristics of the driving simulator that is used for most of our studies.

Besides giving an overview of related theories, concepts and works, this chapter contributes to answering RQ1. We observed that several parameters are commonly used to display information using ALDs. For example, the colors “green” and “red” are commonly used to encode something good (green) or dangerous (red). Urgent information, e.g., warnings, are usually implemented best with red blinking lights. Another example is that color is not important to visualize spatial information using lights.

In the following chapters, we further investigate which parameters are suitable for displaying critical information (RQ1), if the cues affect driving performance positively (RQ2), and look into the effect of ALDs on gaze behavior (RQ3) to validate if ALDs are mainly perceived using peripheral vision.

4 Exploring ALDs for Driver Assistance Systems

One of the goals of this thesis is to investigate how ALD can be used to support drivers in situations that have a potential to become safety critical. Several assistance systems have been proposed or are commercially available. Still, accident statistics do not show a strong decrease. Towards developing more effective ADAS displays, we investigate using ALDs. Most of the current ADAS do not use ALDs or try to address the driver's periphery. We derive from related works that ALDs have the potential to inform drivers without distracting them from their primary task of driving and thus improving their performance.

In this chapter, we present studies that help to understand in-vehicle ambient light patterns and driver expectations towards them. We first present an online study that explores suitable locations for ALDs. Afterwards, we cover the assistant systems listed below. In addition, we summarize related works that used light patterns but are not in the scope of this thesis at the end of this chapter.

We focus on four use cases with already existing ADAS. All four are representative for situations in which ALDs could keep drivers continuously informed without making them focus on the display. The following list motivates these use cases. We will give more details about them in the corresponding sections.

Navigation Navigation devices are common nowadays. In contrast to the other systems in this chapter, they do not indicate a distance to another object but give navigation instructions. These instructions must be given at the right time and location to be understood well, but they must not interfere with more critical driving tasks. We assume that drivers need to focus away from the street less with ALDs (see Section 4.2).

Reverse Parking Reverse parking is a driving task that takes place at low speeds. However, drivers have to focus on the rear end of the car while also maintaining an awareness of their surroundings. With ALDs, drivers could stay informed on the distance to rear obstacles in the periphery and could focus on other areas (see Section 4.3).

Forward Collision Warning Many drivers do not maintain a safe gap to forward vehicles, risking severe accidents. ALDs could continuously inform about the current gap without being annoying or distracting. Further, an ALD could be designed to grab the drivers' attention if the gap becomes dangerously close while they are focusing somewhere else (see Section 4.4).

Changing Lanes Before changing lanes, drivers must assess the gaps to the surrounding vehicles and their ability to control the vehicle appropriately. In highway driving, mistakes or misjudgments in this task lead to severe accidents. Again, an ALD may help to continuously keep drivers informed about gaps while only grabbing their attention when needed (see Section 4.5).

The works in this chapter are usually limited to one HCD iteration because the goal was to explore the designs and mainly contribute to the research questions RQ1 and RQ2. The exception is changing lanes for which we explore designs in this chapter, before investigating it deeper in the following one.

4.1 Placement of In-Vehicle Ambient Light Patterns

Before looking into the different assistant functions, we looked into driver expectations towards in-vehicle ambient light displays and report the results in this section. An initial subset of these results is published in [LMHB13].

4.1.1 Online Survey

Towards the development of an ALD, we needed to find out where to place it. We did a brainwriting session with five drivers and extracted nine locations. Based on that, we realized prototypes at these locations. Based on videos and pictures of the prototypes, we created an online survey to answer the following: Where do participants think it was easy to perceive a light display ($Q1$)? Where would participants prefer to have a light display placed ($Q2$)? Snapshots of the displays are shown in Figure 4.1.

We took this approach to receive feedback from more participants, compared to performing a lab study. While doing so, one has to keep in mind, that the dynamics of ambient light cannot be mapped to images. Hence, the answers may differ from results coming from a real in-car setting. However, we will be able to focus on a few locations while evaluating different light behaviors in future work.

4.1.1.1 Procedure

After an introduction to the objective of the survey, the questionnaire asked for personal information, such as age or gender. Next, participants could watch videos of various light patterns at different locations to get an impression of what is possible. They were reminded that the survey is about locations of a light display and not about these light patterns. For each location shown in Figure 4.1, an image consisting of seven examples of light patterns was presented. Participants could rate each location for its perceptibility ($Q1$) and their preference ($Q2$) using a seven-point Likert-type scale and comment on it. Afterwards, participants were asked to select their favorite or the option *none of the shown*. In addition, they could sketch their ideas for a location and comment on it. Finally, they could give general feedback regarding the survey.

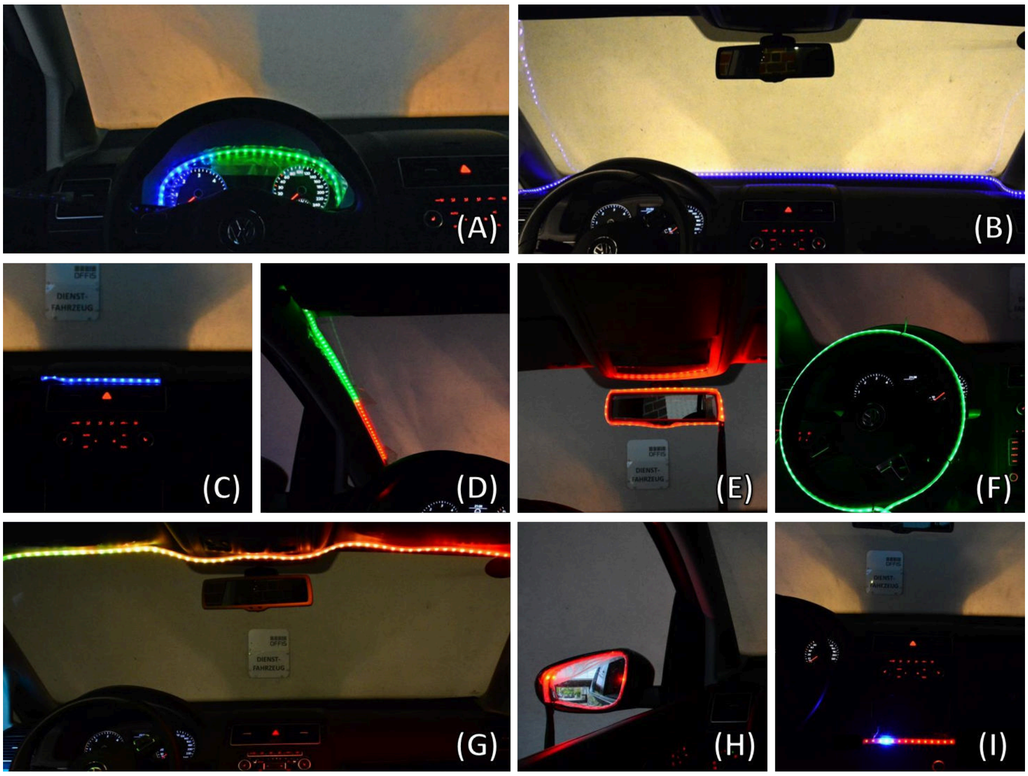


Figure 4.1: Locations for the ambient light display. A: at the dashboard. B: below the windscreen. C: above the central console. D: along the A-pillar. E: at the rear-view mirror. F: at the steering wheel. G: above the windscreen. H: at the side-view mirror. I: below the central console.

4.1.1.2 Results

The survey was completed by 60 people (39 male, 20 female, 1 without answer). Most of them (25) were between 24 and 30 years old. Also, most of them (20) received their license 5 to 10 years ago. Seven participants stated they do not drive, 12 drive less than 5,000km per year, 16 up to 10,000km, 13 up to 20,000km and 12 more than that.

Perceptibility and Preference

We used Friedman tests to evaluate the significance of our effects regarding $Q1$ and $Q2$. Also, we performed Wilcoxon signed-rank tests to follow-up our findings and applied Holm corrections. Effect sizes were calculated using the formula $r = \frac{Z}{\sqrt{N}}$, where N is the total number of the samples, and among other results shown in Table 4.1.

Likings and perceptibilities differed significantly ($\chi^2_l(8) = 97.91, p < .001$, $\chi^2_p(8) = 138.78, p < .001$ respectively). *The dashboard (A)* is the favorite location for 18 people.

		Likings					Perception					
ID	Fav.	Mdn	IQR	r_{lA}	r_{lB}	r_{lC}	Mdn	IQR	r_{pA}	r_{pB}	r_{pH}	r_{pI}
A	18	5	3		.30	ns	5.5	2.25		ns	.54	.53
B	10	5	4	-.30		ns	6	2.25	ns		.49	.52
C	8	5	4	ns	ns		5	3	- .28	ns	.40	.54
D	5	4	3	-.35	ns	ns	5	2.25	ns	ns	.48	.46
E	4	4	3	-.39	ns	ns	4	1.25	- .37	- .32	.40	.41
F	4	3	3	-.47	-.30	-.34	4	2.25	- .42	- .35	.35	.38
G	2	4	3	-.47	-.31	ns	5	3	- .38	- .36	.39	.45
H	2	2	3	-.47	-.31	-.34	2.5	3	- .54	- .49		ns
I	1	2	3	-.50	-.38	-.52	3	2	- .53	- .52	ns	

Table 4.1: Number of votes for favorite location (Fav), medians (Mdn) and inter-quartile ranges (IQR) for perceptibilities and likings, and effect sizes (r_{pX}, r_{lX}) for significant differences to other locations ($p < .05$ after Holm correction). Non-significant effects were marked with "ns" or not included in the table. The names of the rows refer to the names of the locations given in Figure 4.1.

Next, 10 participants preferred *below windscreen (B)*. Similarly, *(A)* is significantly more liked than all other locations, apart from *above the central console (C)*. *(B)* and *(C)* were both liked more than *(F)*, *(H)* and *(I)*. Also, *(B)* received a better rating than *(G)*.

The dashboard (A) was also scored to be significantly more perceivable than all other locations, apart from *(B)* and *(D)*. *(A)* and *(B)* were rated more perceivable than *(E-I)*. *The side-view mirror (H)* and *below the central console (I)* are assessed worst. The perceptibility of both locations is rated significantly lower than that of any other location but does not differ between the locations.

Comments

Participants were asked to comment on each location and light displays in general. Independent from the location, three participants were concerned that a light display may be overwhelming or distracting for drivers or others. Similarly, one person pointed out that drivers should not be able to look into the LEDs directly. Another one pointed out that the light needs to be unobtrusive when there is no danger, while it should be bright to get the attention.

Some general remarks were repeated for several patterns. For example, one person mentioned that no presented pattern offered 360 ° visibility. Another participant repeatedly mentioned that switching the driver's attention towards the light had no benefit ins critical situations. Also, one comment pointed out that the light should not blink or be always active to avoid habituation of the driver. We summarize the specific stated benefits, drawbacks and use cases per location below.

Dashboard This location (see Figure 4.1(A)) received the most positive feedback. Besides general comments like “optimal position”, five participants pointed out that it is a good location because it is close to the line of sight and drivers are already used to receiving relevant information from there. Also, three people stated that this location is beneficial because it is already illuminated and not visible for other traffic participants. Thus, light at this location does not increase distraction. On the other hand, three people pointed out that there is already much information at this location which may complicate interpretation. Still, one person stated that he or she is not looking very often towards this area. This location may be most suitable to warn drivers and highlight close by instruments.

Below Windscreen Similarly to the location at the dashboard, people liked most often that this location (see Figure 4.1 (B)) is close to the line of sight, as pointed out by four people. Three participants assessed the display to be too obtrusive during normal driving. Two people were concerned about the LEDs being difficult to perceive on the far right side. One person pointed out that LEDs at this location may blind the driver. One participant explained that this location might be best to give information in critical situations. Another one mentioned that the display could be used to visualize speed with different colors.

Above Central Console This location (see Figure 4.1(C)) shares some of the benefits of the dashboard. Again, participants pointed out that it is a good trade-off between perceptibility and risk of distraction. Also, drivers are already receiving information from this location. However, this location is not as close to the line of sight. Further, already having information at this location may also interfere with the information of this light display. The most suitable application at this location seems to be navigation assistance. Further, one participant explained that this location is not suited well for critical information because the location does not make it clear to which danger a warning may refer to.

Along A-Pillar Six participants mentioned that this location (see Figure 4.1(D)) was good, while six think that lights at this location would be too distracting or may blind the driver. The location is considered to be useful to display warnings. However, one person was concerned that light on the A-pillar might discourage drivers from looking into that direction.

Rear-View Mirror The perceived benefits of placing ALDs at the rear-view mirror (see Figure 4.1(E)) are that they are perceived easily but do not distract according to two participants. Further, it is considered beneficial that this location is close to the line of sight for some driving tasks. However, six people commented that the lights at this location might be distracting. One person stressed that it could also distract drivers of other cars. Analogously to the locations discussed above, participants stated that warnings could be useful at this location. A possible use case is to visualize the distance to rear obstacles during reverse driving.

Steering Wheel The only positive comment on the steering wheel (see Figure 4.1(F)) was that the light is hard to perceive from the outside. Nine participants commented that lights might be distracting at this location. Three pointed out that information could be hard to perceive because drivers are not looking in this direction. Further, one driver was concerned about the light distracting other drivers. Use cases at this location are navigation assistance and warnings.

Above Windscreen No participant commented anything positive about this location (see Figure 4.1(G)) . Here, lights are assumed to be difficult to perceive, especially at the right A-pillar. They may also distract, annoy or blind drivers. It was also mentioned that they might feel urged to look upwards which could annoy them. Further, it may not be a suitable position in convertible cars. Still, one person considered this location to be useful for warnings in critical situations.

Side-View Mirror According to the participants, this location (see Figure 4.1(H)) may make the driver look more often into the mirror. Thus, it is an appropriate location for displaying information in situations in which drivers need to look into it. Negative aspects include that it may distract the driver (5x) and traffic participants outside the vehicle (4x). Also, this location is considered to be problematic at bright sunlight. In addition, some comments stressed that indicator lights and blind spot warning systems are already located there.

Below Central Console Two participants mentioned that this location (see Figure 4.1(I)) is good because it does not distract drivers. Six people commented that it would be difficult to perceive information from this location because a driver is not looking there. Also, three mentioned that light at this location could distract drivers. Furthermore, this location was perceived as not beneficial because it is not close to critical information and may be confused with lighting for infotainment devices located there. Nobody suggested a use case for this area.

Sketches

Ten participants sketched displays near the dashboard and can be summarized as variations of the dashboard location (A). An example is shown in Figure 4.2(a). They often modified the display to be further above and not so much hidden behind the steering wheel. Eight people proposed to use a head-up display between rear-view mirror and

(a) At the dashboard. (b) Head-Up Display. (c) Indirect Lighting.

Figure 4.2: Examples for sketches of the participants. The black outline was already given, and the only available color was yellow.

steering wheel as an alternative to the proposed locations (see, e.g., Figure 4.2(b)). Three participants suggested some kind of indirect lighting, as shown in Figure 4.2(c). According to them, light patterns at this location can be symmetrical and direct the driver's attention to different directions around him or her. Three suggested variations on the lower windscreen location (B). All of them suggested placing it not at the windscreen but closer to the driver. One person suggested placing LEDs all around the windscreen, and one proposed to use the lower half of the A-pillar (D).

4.1.2 Discussion

Although most of the locations were rated positively concerning preference and perception, many people expressed their concerns about blinding or distracting drivers and other traffic participants. The most often proposed use case for ALDs was warning drivers except for "at the steering wheel (F)" that may help best during navigation. More specifically, ALDs may be used to direct the driver's attention towards needed information close to the display.

In general, it seems like displays that were located close to the center of the road were rated as more likable and perceivable than displays that were located further away. Participants preferred the location at the dashboard (A) were usually most information about the car's status is located while it is also close to the forward area. Similarly, below the windscreen (B) may direct the driver's attention towards different areas in front of the driver. Below the central console (I) received low ratings and was not connected to any use case. The side-view mirror (H) received comparably low ratings. Not many use cases for an ALD at this location have been proposed, often instead stressing this location's potential for distracting other traffic participants.

Overall, this questionnaire is limited by the unrepresentative sample of participants. Still, people often pointed towards interesting characteristics of the light display loca-

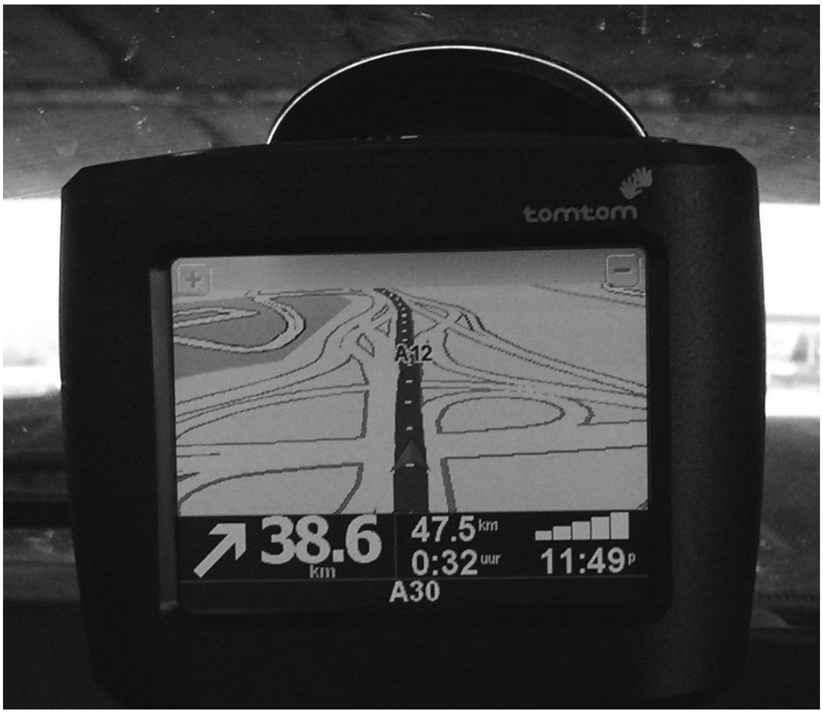


Figure 4.3: *An example of a navigation device. By Kliek (`https://commons.wikimedia.org/wiki/File:TomTomOne.jpg`), "TomTomOne", `https://creativecommons.org/licenses/by-sa/3.0/legalcode`.*

tions that should be considered. The main takeaway for the remainder of this dissertation is that in-vehicle ambient light displays should be located close to the information that they should highlight and not blind or distract people.

4.2 Navigation Assistance

Navigation devices have the potential to decrease a driver's workload by providing navigation instructions. The challenge when developing such a system lies in providing information at the right time without distracting the driver from more critical driving tasks like staying in the lane. Commercial systems, such as TomTom One (see Figure 4.3), or Google Maps usually provide the current route and next navigation instruction via a dedicated screen and spoken instructions. Furthermore, modern built-in navigation systems usually provide the next instruction as symbol or map overlay in the dashboard, behind the steering wheel. Drivers typically glance frequently towards these displays, which can cause distractions [TLCC15].

Besides the visual modality, previous research also looked into alternatives like sound, vibration, or ambient light. For example, Kun et al. compared navigation systems that were using speech or speech plus visual cues on an LCD screen and found that using only speech enhanced the driving performance in terms of lane position and fewer glances off the street [KPM+09]. Kern et al. investigated vibro-tactile navigational cues in the steering wheel [KMH+09]. Their results suggest that auditory cues may assist better than vibro-tactile ones in a distracting environment. On the other hand, using a multimodal display including visual and vibro-tactile signals led to better driving performance than unimodal ones. Head-up displays (HUDs) may be another way to reduce the time a driver has to glance away from the street. For example, Kim et al. found that participants made fewer navigation errors while using the HUD instead of an LCD screen [KD09].

Ambient light is a modality that has not been evaluated much for navigation. Therefore, we developed and tested ambient light cues for turn-by-turn navigation [MLEA+16]. We summarize the results in this section. Our goal is to investigate which parameters of an ALD are suitable to encode navigational cues (RQ1) and assess if drivers navigate effectively (RQ2) in terms of avoiding navigational errors. Further, we investigate if it affects gaze behavior (RQ3).

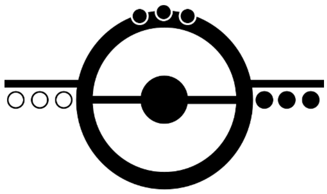
We applied the following approach to this research. First, light patterns are designed based on the results of a focus group session. Second, participants of an online questionnaire rated the suitability of the developed light patterns for navigation based on videos. Third, we realize and explore eight light patterns in a driving simulator study to find the most helpful design. Finally, four implementations are evaluated against each other: two conditions that use the ALD and two that use a graphical user interface (GUI). We found that ambient light cues are well accepted and reduce the cumulative glance time away from the street ahead, while navigational errors did not change significantly.

4.2.1 Ideation

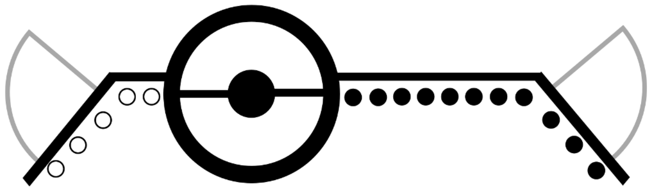
Within the ideation phase, we conducted a brainwriting workshop, including discussions, with five car drivers (three female) to generate ideas. Additionally, we interviewed two drivers to discuss the design ideas in more depth.

In both settings, we handed out ten cards with navigation levels, based on the work of Prasad et al. [PTGH14]: three directions (left, right, U-turn) at three times (approaching, get ready, turn now) and an additional “go straight ahead”. Also, we visualized different levels of brightness and blinking or pulsating frequencies utilizing a simple prototype (see Figure 3.4).

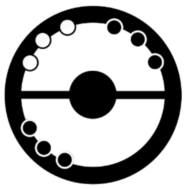
Following the brainwriting protocol (see Section 2.2), the drivers were asked to write their ideas for ambient light patterns down and pass it to their neighbor. The process stopped after about 30 minutes. Afterwards, we collected the ideas, structured them, and discussed them with the participants.



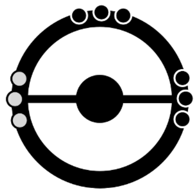
(a) LP1, LP2, LP3 and LP5 use a few LEDs next to the steering wheel. The difference between these pattern is the brightness progression and the used colors (white for LP1-LP3, yellow/green for LP5).



(b) LP4 uses the area between steering wheel and B-pillars. Depending on the next turn, the area left or right of the steering wheel first pulsates moderately (approaching phase). In the “get ready” phase, the LEDs are activated sequentially, before they start to pulse fast in the “turn now” phase.



(c) LP6 uses LEDs on the steering wheel. A light cue moves moderately fast from top to left or right along the steering wheel in the “approaching” phase. The cue moves fast in the “get ready” phase. The top left or right quarter blinks to indicate “turn now”.



(d) LP7 uses LEDs on the steering wheel locatated on the top, left and right. The left or right area turns yellow in the “approaching” phase and starts to blink to display “get ready”. The corresponding side turns green to indicate “turn now”.

Figure 4.4: Proposed locations of the ALD for navigation. The white, black and green dots represent areas for LEDs. All patterns are located around the steering wheel and are displaying a left turn in these sketches. Apart from LP5 and LP7, the patterns do not rely on color to encode their states. LP3, LP4, and LP6 use moving lights, the other patterns rely on blinking, pulsing or static lights.

Results

Seven distinct light patterns emerged from the brainwriting and interviews. Their locations are depicted in Figure 4.4. Usually, the light cues are activated analog to the direction of the next turn, activated on both sides for U-turns, and stay off when suggesting continuing straight ahead. An exception is LP5 (see Figure 4.4(a)), which suggests continuing straight ahead with a green light on top of the steering wheel. Also, LP7 (see Figure 4.4(d)) uses a moderately blinking red light on the left side to suggest a U-turn.

LP1 uses a linear fade-in in the corresponding direction to encode the “approaching” phase. LP2 displays this phase with a slow blinking cue. Both encode the “get ready” phase with moderate blinking and the “turn now” phase with fast blinking lights. LP3 and LP4 use the size of the light cue for navigational cues. LP3 increases the size of active LEDs towards the corresponding direction during the “approaching” and “get ready” phases until all LEDs on the corresponding side are turned on. A light cue repeats moving away from the steering wheel in the “turn now” phase. In LP4, a light cue moves towards the B-pillar in the “approaching” phase. The light fills up from the steering wheel towards the B-pillar in the “get ready” phase. The outmost LEDs pulse in the “turn now” phase. LP5 and LP7 use static yellow lights at the left or right to indicate the next navigation point, moderately blinking yellow lights for “get ready”, and static green lights for “turn now”. LP6 uses a repeatedly moderately fast moving light cue that moves from top to left or right to encode “approaching”. The speed increases for “get ready”. The “turn now” phase is indicated with blinking lights.

4.2.2 Assessing Designs

We conducted an online questionnaire to assess the suitability of the light patterns. The questionnaire consisted of a video of the light pattern, a five-point Likert scale to rate the suitability and a text area for feedback and comments per each of the seven light patterns. Also, we asked participants to rank the light patterns from most suitable to least suitable. We summarize the most relevant results in the following. A more detailed analysis per each pattern can be found in [MLEA+16].

We received 25 complete responses that in summary showed that LP1, LP5, and LP7 are most suitable. 16 participants reported that they do not need a cue for continuing straight ahead, which was part of LP5. Five participants preferred to have the color change to green (LP5 and LP7) between “get ready” and “turn now”. Also, 19 people remarked that the LEDs should not be placed on the outside of the steering wheel (e.g., LP7) because drivers may cover the display with their hands.

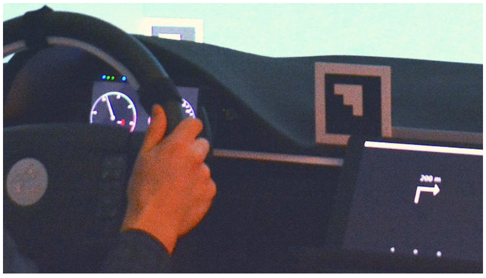
4.2.3 Prototypes for Evaluation

Considering the results of the previous phases, we define three main parameters with two levels to design light cues for navigation. The most suitable color encoding for the three states seem to be yellow, yellow, green (YYG) or white, white, green (WWG). The brightness function is either static, blinking, static (SBS), or static, blinking, blinking (SBB). Further, the most suitable location is either on the steering wheel (OSW, Figure 4.5(b)) or next to the steering wheel (NSW, Figure 4.5(a)). We implemented all eight combinations of these parameters as light patterns using LED strips with a resolution of 72 LEDs per meter next to and onto the steering wheel (see Figure 4.5(a) and 4.5(b)).

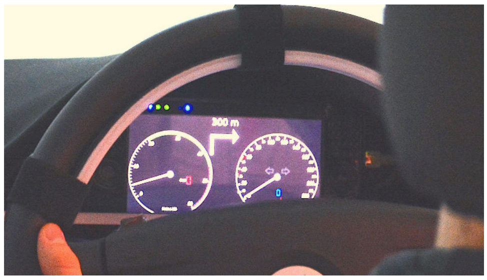
We tested the suitability of each of the eight patterns in a driving simulator study with 24 participants. The simulated city consists of 7x7 blocks in a grid layout with a speed limit of 50km/h. We placed roundabouts at the end of each street, where drivers could do a U-turn. No other traffic participants are simulated. We used a repeated measures design

(a) ALD next to the steering wheel (LNSW).

(b) ALD on the steering wheel (LOSW).



(c) GUI next to the steering wheel (GNSW).



(d) GUI behind the steering wheel (GOSW).

Figure 4.5: Locations for the ALDs used in the exploratory study and the evaluation and the GUIs used in the evaluation.

for the experiment and presented the eight patterns in a counterbalanced order. Each trial consisted of 12 maneuvers in randomized order: 4 directions with three repetitions each. Each light pattern's helpfulness and distraction was rated utilizing 5-point Likert scales after each trial. At the end of the study, we asked participants to rank the patterns and explain their reasoning.

Results

As summarized in Table 4.2, all error rates are below 5% overall. P2 and P6 were ranked highest. They only differ in their location. P2 is the only light pattern that received a rating for helpfulness below a median of four. On the other hand, P2 is the pattern with the lowest distraction score (Mdn: 1), while P7 received the highest (Mdn: 3). Overall, white was preferred over yellow color in the first phases because it was easier to distinguish from green. Further, static light was preferred over blinking light in the "turn now" phase to make the change of states easier to recognize with peripheral vision. Because the results did not clearly indicate which location should be preferred, we decided to run the evaluation with both most promising patterns: P2 and P6.

Pattern	Colors	Brightness Function	Position	Error Rate	Helpfulness (Mdn)	Distraction (Mdn)	Times ranked as best
P1	🟨🟨🟩	SBS	NSW	4.17%	4	2	1
P2	⬜⬜🟩	SBS	NSW	4.17%	3.5	1	7
P3	🟨🟨🟩	SBB	NSW	1.39%	4	2	-
P4	⬜⬜🟩	SBB	NSW	0.69%	4	2	1
P5	🟨🟨🟩	SBS	OSW	0	4	2	4
P6	⬜⬜🟩	SBS	OSW	2.78%	4	2	9
P7	🟨🟨🟩	SBB	OSW	2.08%	4	3	-
P8	⬜⬜🟩	SBB	OSW	0	4	2	2

Table 4.2: Overview of the eight light patterns for the exploratory study. SBS: static-blinking-static, SBB: static-blinking-blinking; NSW: next to the steering wheel; OSW: on the steering wheel.

Navigation Method	**Glance Duration**		**Glance Frequency**		**Acceptance**		**Demand**	
	M	SD	M	SD	Mdn	IQR	Mdn	IQR
GOSW	9.19	7.74	59.90	23.22	3.0	1.0	2.5	2.25
GNSW	14.45	8.38	48.91	22.99	2.0	1.0	3.0	2.00
LNSW	2.29	3.42	11.67	15.28	4.0	2.0	2.0	1.00
LOSW	1.42	2.12	8.00	12.25	4.0	1.0	1.0	1.00

Table 4.3: Summary of the evaluation results. Acceptance: 5 - very acceptable, Demand: 5 - very demanding.

4.2.4 Evaluation Against Navigation Assistance with GUI

We decided to take the two most promising light patterns (see Figures 4.5(a) and 4.5(b)) and evaluate them against similar screen-based systems that present the same information (see Figures 4.5(c) and 4.5(d)). We hypothesize that using ambient light cues will decrease the time spent looking towards the navigation aid without increasing the number of navigational errors.

The apparatus and driving tasks are similar to the ones in the exploratory study. The differences are the used navigation aids, the use of head-worn eye trackers, and that we asked for rating acceptance and demand instead of helpfulness and distraction.

Results

We recruited 24 people (13 female) for this experiment. The results are summarized in Table 4.3. Details are given in [MLEA+16]. The light-based navigation aids performed better than the systems with GUIs. The light pattern on the steering wheel (LOSW) performed best. Overall, using ALDs led to significantly shorter glance durations and a lower glance frequency, while the ALDs did not differ significantly. The error rates were 2.08% for GOSW, 1.39% for GNSW, 1.39% for LNSW, and 0% for LOSW.

The participants rated the acceptance significantly higher and the demand significantly lower for both ALDs compared to the GUIs. However, only the effect on “demand” differed significantly between the light displays. In line with the ratings, LOSW was twelve times (50%) ranked best, LNSW seven times, GOSW four times, and GNSW once.

The interviews after the experiment revealed that participants trusted the navigation system and could imagine using it in their cars. Most participants (21 of 24) preferred to have an additional modality for more details in complex scenarios, such as choosing the right lane.

4.2.5 Discussion

Overall, participants showed a positive attitude towards the light-based systems. Furthermore, the results contribute to answering the research questions positively as summarized in the following.

4.2.5.1 Which Parameters Can Be Used for Navigational Cues?

The studies in this work confirm that white color works well to display neutral information, such as an upcoming maneuver, while green color is preferred to distinguish neutral information from a call to action, such as “turn now”.

In line with the results of our previous online questionnaire (see Section 4.1), participants preferred the information to be presented close to the line of sight relevant for the task. In this case, in front of the driver for the navigation task.

Our results indicate that distinct patterns per phase are preferred over fading from one state into another. Moreover, participants preferred to only have a blinking light in the “get ready” phase, while the light should stay static in both other phases to not distract.

4.2.5.2 How Effective Are ALDs Compared to GUIs?

We hypothesize that utilizing ambient light reduces the perceived demand and distraction of the display during driving because it can be perceived with peripheral vision. The exploratory and evaluation experiment showed that the number of navigational errors is low. When compared to the GUIs, participants reported a lower perceived demand with both light displays and misinterpreted the navigational cues less often.

Figure 4.6: An example of a park distance control system from VW. By Nozilla (`https://commons.wikimedia.org/wiki/File:Parking_Assist.jpg`), "Parking Assist", `https://creativecommons.org/licenses/by-sa/3.0/legalcode`.

4.2.5.3 How Is a Driver's Gaze Behavior Affected by ALDs?

If ALDs are perceived with peripheral vision, we expect to observe a decrease in glance durations and frequencies while driving performance is not affected negatively. This assumption is supported by the results of our evaluation.

4.2.6 Future Directions

The driving simulator studies in this work are limited by the simple street layouts and the missing traffic participants. We decided for this setup to evaluate if ALDs can be used for navigational cues without adding noise to the measurements. We expect to observe similar or stronger effects in more complex setups as our assumptions about ambient light being less demanding and distracting are supported. To investigate if this expectation is valid, future research may increase the complexity of the street layout, add traffic participants, or include other sources that make it more difficult to navigate.

4.3 Reverse Parking Assistance

In contrast to the other discussed assistance systems in this chapter, parking is usually an activity at low speed. However, many accidents happen during parking. For exam-

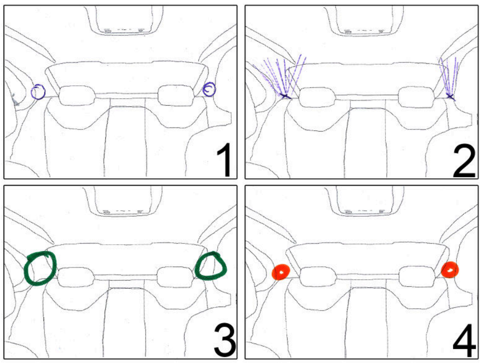
Figure 4.7: The parking scenario. Left: a sketch of the bird's eye view with the driver's car in the starting position. Right: the parking lot.

ple, German transport statistics reported 9,206 accidents with injuries in 2017 that were classified as "accident involving stationary vehicles", which includes accidents during parking maneuvers, in urban areas (4.4% of all accidents in urban areas) [Sta18a]. Ten people were killed in these accidents. According to [Wei17], about 40% of all passenger car accidents with material damage can be classified as a shunt or parking accident.

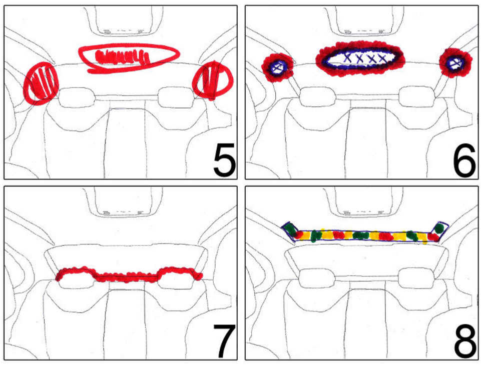
As discussed by, e.g., Seiter et al. [SMK12], parking assistance systems usually use ultrasonic sensors or cameras. The sensor information is used to warn about objects behind or in front of the car, derive and display the distance to objects, or assist drivers by providing an augmented image of the forward or backward scene. Advanced systems can also take over steering [BDF+14, KBS+15]. Commercial systems typically use visual indicators with colors in combination with beeping sounds and different cues per distance level (e.g., [SMK12, KBS+15]). An example is shown in Figure 4.6.

Arguably, current parking assistance systems have two downsides. First, the constant auditory beeping may annoy drivers (e.g., [Doi08]). Second, the visual component is located in front of the driver and thus not visible if drivers turn around to focus on the rear end of the vehicle.

Reverse parking is an interesting scenario for this dissertation because the encoded information has a spatial and a time dimension, and a bad driver performance will result in an accident. The information that needs to be encoded is usually located behind a driver, which covers a direction that is not investigated in the other applications of this chapter. We identified several designs for the light patterns and evaluated one in a driving task in a controlled environment on a parking lot. The results are also published in [HLHB16]. They indicate that our system is easy to use and less frustrating than a commercial park distance control system.



(a) Sketched displays at the C-pillars. Very similar sketches were occluded here.



(b) Sketched light displays between the C-pillars.

Figure 4.8: Design sketches for light patterns that assist during reverse parking.

4.3.1 Scenario

Our scenario is shown in Figure 4.7: a driver wants to revert into a 90° parking space with obstacles around it. The dimensions of the parking lot were prepared according to common parking lot dimensions: 2.5m x 4m. In our setup, the obstacles were represented by empty carton packages, to prevent damage.

4.3.2 User Interviews

In order to find a suitable design for the light display and its patterns, we observed drivers and interviewed them. The participants were observed while they were reverse parking a car into a parking lot with and without the embedded commercial park distance control (PDC) of a BMW E92. The PDC uses sounds and visual information on a screen in front to display the distance to obstacles. During the maneuvers, participants were asked to report anything of interest, such as any situation where they felt uncomfortable, insecure, or confused by the display, but also positive experiences. Further, the experimenter took notes, e.g., about critical situations. After the parking maneuvers, but still in the car, the participants were introduced to the concept of in-vehicle ALDs by showing example videos. Afterwards, we invited them to sketch a light display and its patterns. Participants were explicitly asked for position, colors and needed features.

Ten people (four female) participated. The preferred location for the display was at the C-pillars (8 people), shown in Figure 4.8(a). Sketches which did not only use the C-pillars are shown in Figure 4.8(b). The preferred light pattern was a traffic light metaphor, i.e., a color change from green to red. Transitions between the colors should be smooth. However, the color should stay the same per distance class. Also, no pulsing or blinking light should be used because it would stress or irritate the driver. Only when

Figure 4.9: Our integrated prototype with light displays at the C-pillars. Left: green (1.5m-2.5m), right: orange (0.5-1.5m).

Distance	**Pattern**	*red*	*green*	*blue*
>2.5m and reverse gear engaged	white	100%	100%	78.5%
1.5 – 2.5m	green	0%	100%	0%
0.5 – 1.5m	orange	100%	62.7%	0%
0.3 – 0.5m	red	100%	0%	0%
<0.3m	blinking red at 1Hz			

Table 4.4: Distance classes and the corresponding colors. If the class changes, a .2s long color-fade is triggered.

the distance to another object is very small, blinking light was demanded to warn the driver. Further, the participants stated that it is not necessary to precisely display the located object but to indicate the direction towards it.

4.3.3 Design of the System

Based on the previous results, we created a prototype that covers the interior part of the C-pillars. An Arduino One controls the implemented display. It is shown in Figure 4.9. Ultrasonic sensors were used to detect the obstacles. The distances are based on the distance classes of the PDC in the used car, a BMW E92, and mapped to colors. In order to achieve smooth transitions, a change of distance classes triggers a 200ms lasting color-fading between the current and the new color. The colors are based on the participants' sketches and given in Table 4.4.

4.3.4 Experiment in Parking Lot

We conducted an experiment with 18 drivers (two female) to assess the effect of the light display on driver's performance, workload, and acceptance. Apart from the new light display, seen in Figure 4.9, the apparatus and scenario remained the same as before and is shown in Figure 4.7.

The participants had to pass three conditions: reverse parking without assistance ("Baseline"), with activated PDC ("PDC"), or with our prototype activated ("ALD"). The order of these conditions was counterbalanced. Each condition was repeated three times. Hence, the amount of iterations per participant is nine.

We measured the duration of a parking maneuver manually. In order to assess the usability of the systems, the participants answered a SUS in the conditions with PDC and light display. The mental workload was quantified using a raw NASA TLX. We also prepared a questionnaire to compare the PDC and light display. The participants rated the following statements on a five-point Likert scale, ranging from "strongly disagree" (1) to "strongly agree" (5):

1. The ALD informed me well about the environment
2. The ALD distracted me
3. I focused more towards the rear of the car
4. The ALD did not provide enough information
5. The ALD pattern was easy to understand
6. The ALD system was better
7. A combination of PDC and ALD would be good

At the end of the experiment, we did semi-structured interviews, asking for strengths and weaknesses of the ALD and general feedback.

4.3.4.1 Results

In the following, we will present and discuss the time it took participants to complete a parking maneuver, the results of the questionnaires and a summary of the interviews.

Time to Complete a Parking Maneuver

Overall and in the first maneuver, participants completed a parking maneuver fastest in the baseline condition, as shown in Figure 4.10. PDC and ALD do not differ much, especially after they experienced the assistance function in the first maneuver.

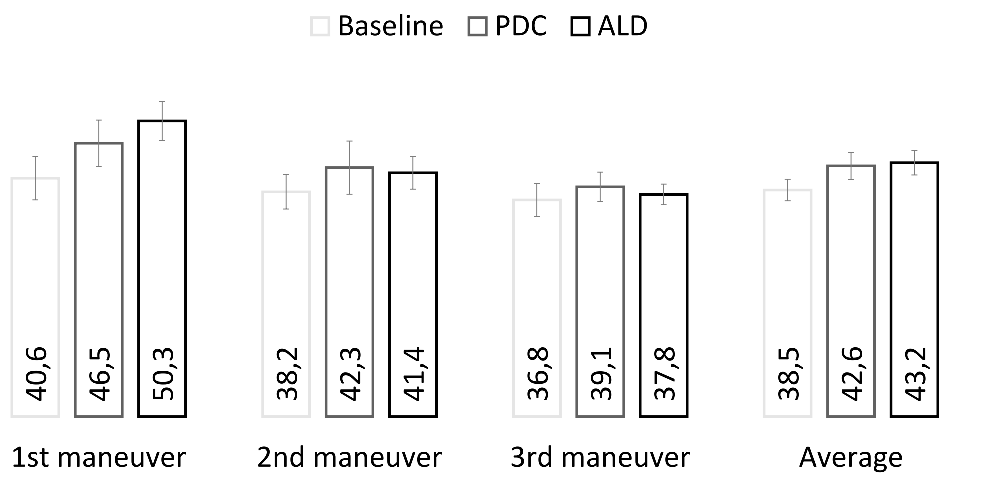


Figure 4.10: Mean time in seconds to accomplish reverse parking maneuver per each iteration and overall with 95% confidence intervals.

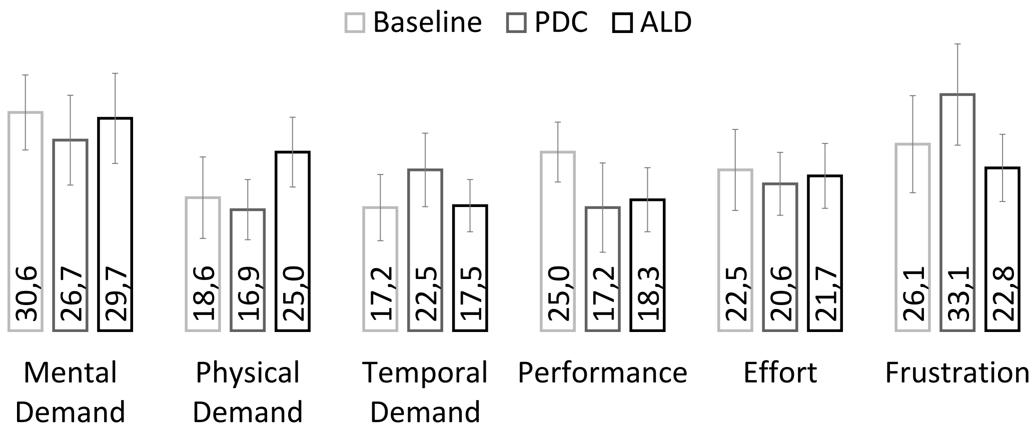


Figure 4.11: Mean values with 95% confidence intervals for each scale on the RTLX.

Questionnaires

The ALD received a good SUS score (M: 71.3, SD: 10). However, the commercial PDC received an excellent score (M: 83.3, SD: 7.8). The individual scales show that the ALD was rated worse than the PDC for every scale.

We did not observe big effects between the conditions in the RTLX. The workload was highest in the baseline condition (M: 23.3, SD: 6). It was marginally lower with PDC (M: 22.8, SD: 6.6) and the lowest with ALD (M: 22.5, SD: 4.8). Looking into each dimension of the RTLX, as shown in Figure 4.11, reveals that ALD led to higher physical demand (M: 25, SD: 10.6) compared to the baseline (M: 18.6, SD: 12.3) and

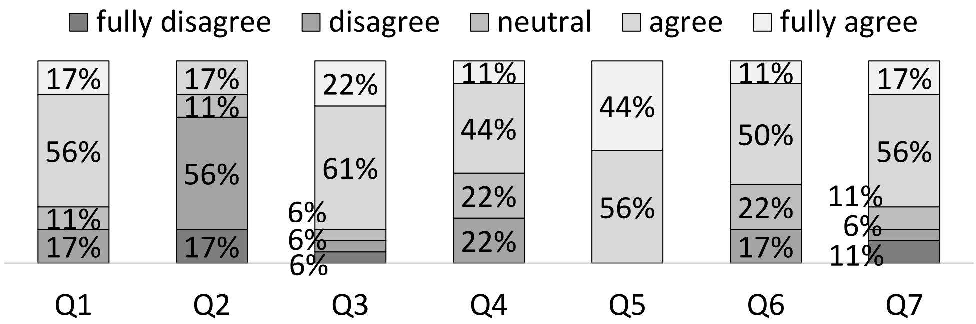


Figure 4.12: Percentage of answers per question regarding ALD. Q1: well informing, Q2: distracting, Q3: more focus to rear, Q4: not providing enough information, Q5: easy to understand, Q6: PDC was better, Q7: PDC and light display should be combined.

PDC (M: 16.9, SD: 9.1). The temporal demand was highest with PDC (M: 22.5, SD: 11.1), compared to the baseline (M: 17.2, SD: 10) and light display (M: 17.5, SD: 7.9). The own performance, scaled from "perfect" at 0 to "failure" at 100, was rated worst in the baseline (M: 25, SD: 9), compared to PDC (M: 17.2, SD: 13.5) and light display (M: 18.3, SD: 9.7). Please note, that this measure ranges from "Perfect" (0) to "Failure" (100). Also, the frustration seems to be different between the conditions: commercial PDC caused a higher frustration (M: 33.1, SD: 15.4) compared to using light (M: 22.8, SD: 10.2) or baseline (M: 26.1, SD: 14.7).

The answers to our questionnaire are shown in Figure 4.12. The results show that the participants felt well informed (Q1, 72% agreed) and not distracted (Q2, 72% disagreed). They focused more towards the rear (Q3, 83% agreed), but felt that the display did not provide enough information (Q4, 56% agreed). All participants felt that the patterns were easy to understand (Q5, 100% agreed), but the PDC was preferred (Q6, 61% agreed). A combination of PDC and ALD would be good (Q7, 72% agreed).

Interviews

The interviews revealed results similar to the questionnaire. However, the participants also mentioned that the main weakness of our system was the increased mobility requirement, as they had to turn around to see the light display. Especially older adults might have problems with this. The majority of the participants suggested a combination of PDC and ALD to get more information when needed. Further, the missing acoustic signals were a problem for eleven participants.

4.3.5 Discussion

The goal of this work was to develop a light display that supports a driver during reverse parking. The results indicate that using either ALD or PDC may lead to comparably fast parking maneuvers after initial learning. However, both did not outperform parking without assistance. Also, these results are limited because the times were stopped manually and only one kind of reverse parking was performed.

Overall, ALD seems to be perceived as well informing and usable, but not as good as the commercial PDC. The RTLX revealed that the ALD was perceived as less time demanding and frustrating than the PDC, but not less than parking without assistance.

The goal of focusing the driver's attention more towards the rear of the vehicle was achieved. However, the participants did not like the increased need to move. One solution to this problem could be to place the light display next to the rear-view mirror, as it was suggested in Section 4.1. Another solution could be to make sure that the display is visible in the rear-view mirror, e.g., by illuminating the area between the C-pillar, as shown in the sketches in Figure 4.8(b).

As participants preferred the PDC over the ALD, a future system may combine both systems. However, as current sounds can be annoying, it remains an open question how to combine the visual and auditory cues.

We showed that an ALD may support reverse parking. However, more research has to be done to outperform commercially available systems. As for other systems in this chapter, participants preferred a traffic light metaphor to encode criticality and placing the display close to the line of sight towards the information (i.e., the obstacle).

4.4 Forward Collision Warning

Forward collisions are a major cause of fatalities in traffic [Win15]. For example, 49,181 accidents on German roads in 2017, or 14% of all accidents that harmed persons, were caused by not maintaining a safe distance to the leading vehicle [Sta18a]. To assist drivers in this situation, forward collision warning systems first use a visual warning, such as displaying a symbol or text, before or along with acoustic warnings to get the drivers attention [Mau12, Win15] as depicted in Figure 4.13. Additionally, tactile cues via deceleration, fastening the seat belt or adding resistance to the gas pedal are used.

The system of Dziennus et al. implements an aspect of this [DKS16]. It warns about too fast speed in relation to the forward vehicle's speed by turning the front area of their display red. Apart from this work, we did not find forward collision avoidance systems utilizing an ALD. Also, as we will discuss in Chapter 5, drivers usually do not maintain a safe gap towards the leading vehicle while preparing a lane change maneuver. Hence, we chose this as a scenario for the work discussed below. This work consists of two parts: deriving design ideas from user studies and evaluating them in the driver simulator.

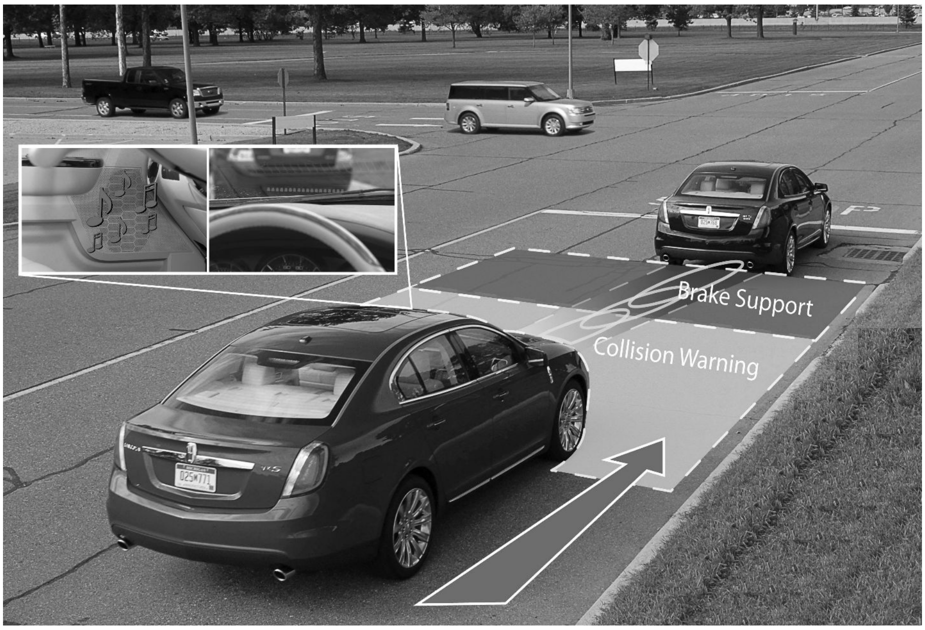


Figure 4.13: The escalation levels of Ford's forward collision warning. This system uses lights and sounds to warn drivers. If the driver does not respond, brake support is activated to support a quicker declaration. By Ford Motor Company from USA (`https://commons.wikimedia.org/wiki/File:Collision_Warning_Brake_Support.jpg`), "Collision Warning with Brake Support", `https://creativecommons.org/licenses/by/2.0/legalcode`.

4.4.1 Ideation

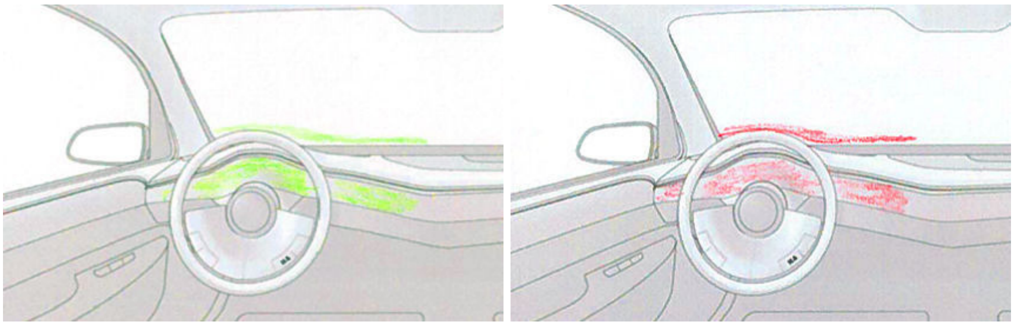
We interviewed 14 drivers (6 female) with a mean age of 27.8 years (SD: 5.9) in a semi-structured way to identify requirements and explore possible designs. We asked for functional aspects and possible pitfalls for designing the system as well as parameters of the light display, such as color, temporal behavior, and location. Furthermore, we asked participants to draw at least one sketch of their idea for a forward collision warning system.

4.4.1.1 Results

In the following, we will summarize the most relevant results of the interviews.

Color

Eleven participants suggested indicating unsafe distance with red color. Green is mentioned by seven people and should indicate a safe gap. Six people suggested using yellow, and three proposed orange. Five people directly suggested using the green to red color space and a traffic light metaphor as also indicated in the sketches in Figure 4.14.



(a) Located close to the dashboard with green lights. (b) Located at the dashboard with red lights.

Figure 4.14: Examples for popular sketches. Green lights are used to visualize a safe gap, red lights to visualize unsafe gaps.

Blue colors were proposed seven times. The mapping would be dark blue for a safe gap to bright blue to indicate an unsafe gap. Other colors are purple (1x), neon colors (1x), or white (1x).

Temporal Behavior

Nine participants proposed to use multiple colors to display the distance. Further, seven mentioned that the transitions should be smooth. Five participants explained that brightness could be used to display the information. Also, five people would like a blinking pattern to visualize a critical distance. Other ideas include increasing the size of the light cue (4x), implement it analog to a "progress bar" (4x), change the saturation of the color (3x), blink continuously (1x), and pulsate (1x).

Location

Eight participants suggested displaying the information at the dashboard. Alternatives are the A-pillar on the driver's side (5x), the driver's door (5x). Other suggestions include the rear-view mirror (3x), the speedometer (3x), the steering wheel (2x), the left side-view mirror (2x), the right front door (2x), and the right A-pillar (1x).

Thresholds

Eight participants suggested starting the display earlier than 1.8s time gap (from the German rule of thumb "halber Tachoabstand"), while five would prefer to only warn if the gap is smaller than 1.8s.

Seven people proposed to start to display the gap earlier if the driver is driving fast, while five preferred to trigger the information display independently from the own speed.

(a) The display at a safe gap. (b) The display at an unsafe gap.

Figure 4.15: The implemented ALD for forward collision warnings.

Other Aspects

Thirteen participants would like to receive an additional sound if the gap is critically small, and four a vibro-tactile cue. Three people would like to have the display disabled when there is no car in front.

Five participants are concerned that this assistant function could increase recklessness. Three people each point out that a light display may distract or shock drivers. Other problems may come from visual impairments (3x), lighting conditions (3x), familiarization (3x), and system failure (2x). Also, drivers may be annoyed by the display (2x) or mistake it for another assistance system (1x).

4.4.2 Design

As shown in Figure 4.15, we used the light display prototype described in Section 3.3.3 to realize the light pattern in front of the driver. We based the designs on the most popular suggestions and implemented a pattern that changes its color from green to red the smaller the gap to the lead vehicle gets: the display activates in green color at a gap of 2.5s. Between 2s and 1.8s, it gradually changes to yellow. Between 1.6s and 1.4s, the display gradually changes to red. Finally, if the gap is smaller than 1.2s, the display starts to blink at an increasing rate in ratio to the decreasing gap.

4.4.3 Evaluation

The driving simulator study is a variation of the lane change discussed in Section 5.1. The scenario consisted of a two-lane highway with a slower car in front, driving at 90km/h and two faster vehicles on the left lane preventing an early overtaking maneuver. The driver's task was to overtake the slower vehicle or decelerate if that was not possible.

We argue that this scenario is an excellent example of a situation in which a driver does not focus enough on the forward gap. Thus, we hypothesized that displaying the gap towards the front vehicle frees cognitive resources to focus on taking the right decision. This hypothesis would be supported by fewer initiations of unsafe maneuvers, as well as a bigger gap to the leading car.

We realized the study as a within-subjects experiment with two conditions: driving with ALD and baseline driving (BL) without assistance. After a short introduction to the experiment, participants would drive in both conditions in counterbalanced order and a break in between. Each condition consisted of 15 training trials that we did not evaluate, followed by a break and 40 driving trials in randomized order. We instructed the participants to accelerate to 120km/h at which a cruise control would take over to keep the trials comparable. We varied initial distances of the car in front as well as speeds and distances of the rear vehicles to create 20 unique trials that were repeated twice per person and condition in randomized order. After the experiment, participants were asked to answer a SUS to rate the usability of the ALD.

Results

26 people (9 female), with a mean age of 25.3 years (SD: 4.6) participated in this experiment. Overall, the display received an excellent SUS score (M: 86.54, SD: 9.63). In total, the participants braked in 11.9% of the trials with BL, and 13.6% with ALD. When they decided to brake, the mean time gap was 1.48s with BL (SD: .45), and 1.47s with ALD (SD: .32). When participants decided to overtake, the mean gap to the lead vehicle is 2.78s in BL (SD: .87), and 2.62s with ALD (SD: .85). They usually initiated the overtaking maneuver shortly after the first car has passed. When they started the maneuver, the mean gap was .48s with BL (SD: .41) and .55s with ALD (SD: .43). The mean gap to the second car, behind the driver's vehicle, was 2.27s with BL (SD: .48) and 2.19 with ALD (SD: .53).

Discussion

Although the display was rated positively, we did not perceive a significant effect on the distances. Thus our hypothesis cannot be supported. It seems like drivers were already well aware of the gap towards the leading vehicle. More research has to be done with a more demanding driving task to assess if this display supports the driver.

4.4.4 Summary

We developed a forward warning system and tested it in a driving simulator study. The results of the design phase are in line with our earlier studies, supporting that drivers prefer traffic light metaphors to indicate safe and unsafe situations. However, the implemented light pattern did not affect driving performance as drivers are also performing well without the interface.

Figure 4.16: *An example of a blind spot indicator symbol, integrated into the side-view mirror. By Michael Sheehan (`https://www.flickr.com/photos/hightechdad/28040296827`), "Blind Spot Indicator - 2018 Chevrolet Tahoe 4WD Premier RST Photos", `https://creativecommons.org/licenses/by/2.0/legalcode`.*

4.5 Supporting Drivers' Lane Change Decision Making

In this section, we first discuss related works on blind spot warnings and LCDAS. Afterwards, we present light patterns that we developed in a participatory design process with human-computer interface experts to explore the design possibilities. This section extends our preliminary discussion of the results in [LMHB14b]. With this work, we aim to find intuitive light patterns that do not only warn drivers when the situation became critical. In contrast, our light patterns should keep the drivers informed to assist them in deciding if a gap is big enough to start a lane change maneuver. This work contributes to the dissertation by looking into suitable parameters (RQ1) for the lane change maneuver. Further, this work is the basis for Chapter 5 that focuses on this driving task.

4.5.1 Lane Change Decision Aid Systems in Related Works

The lane change maneuver is a complex task that requires lateral and longitudinal control simultaneously and is considered being one of the most dangerous driving maneuvers [Hen10]. LCDAS, as defined in ISO 17387, are designed to give warnings with three main functions [ISO08]: "Blind Spot Warning", 'Closing Vehicle Warning", and "Lane Change Warning". The first warns about vehicles in the blind spot, the second about vehicles that approach from behind, and the third combines both. Current modalities for LCDAS include visual elements (e.g., [Aud11, REG02]), acoustic signals (e.g., [Dai10, MKKM08]), or vibration (e.g., [BMW, LBHB15]). As discussed by Bartels et al. [BMS12], most commercial systems only implement the blind spot warning (e.g., Figure 4.16), but not the lane change warning.

The earliest work based on light is “Visionsense; An Advanced Lateral Collision Warning System” from van Dijck and van der Heijden [vDvdH05]. The authors describe four different modalities, which use a feedback or warning signal, and conducted a web-based survey to find situations in which their system is suitable, and to find an appropriate interface design. Among icons and haptic or auditory signals, the light cues were described as a “red light near both side-view mirrors” [vDvdH05] for the warning signal and a “green light near both side-view mirrors” [vDvdH05] for the feedback. They found that their system *VisionSense* “is most useful when it provides a warning signal during a highway lane change” [vDvdH05]. Other mentioned situations were warnings or feedback while *merging*, *passing an intersection*, *getting in a lane*, *parking* and *detect cyclists and moped drivers*. When comparing disturbance and perceptibility, light as a modality revealed the best trade-off. Based on the results the authors developed a model and stated that using the light display would result in fewer lane changes because the driver was aware of the position of the other vehicles. However, these results were not validated in an experiment.

Danielsson et al. [DLB+07] investigated designs for lane change assistance and lateral collision warnings. The lane change assistant was realized with an amber or red symbol in the side-view mirror, depending on warning level. If a lane change intention is detected and a vehicle is in the blind spot area, the warning consists of the red blinking symbol and a warning sound from the corresponding direction. If there is no lane change intention, the symbol is amber without blinking or sounds. In order to warn about lateral collisions, a red light blinks in the A-pillar. Furthermore, three LEDs are included in the rear-view mirror. An amber LED in the middle indicates a notification about a closely following car, while a warning is triggered with all LEDs turning red. The proposed designs are based on previous research with mock-up tests, in a driving simulator and a research car. However, no results were reported.

The work of Roelofson et al. [RBJvA10] focused on a lane change model which uses various inputs to infer a safety degree. They proposed to indicate this degree using five LEDs. Each LED represents one degree with a distinct color: The first LED is red and activated at a safety level of 67.3%. The fifth LED turns green at 99.9%. The three LEDs in between are activated at different levels with colors between green and red via orange. However, neither the location of the LEDs nor the exact colors or brightness levels were given.

Recently, Dziennus et al. [DKS16] proposed light patterns for a ° light display to support several driving maneuvers. Their display is divided into four segments: front, left, right and the rear end of the car. Each segment can indicate actions to the driver: a red light indicates “stop current maneuver on this side”, a red blinking light indicates “stop maneuver immediately”, a green light indicates “start maneuver”, and a green blinking light indicates a more salient recommendation to start the maneuver, if a driver did not react after 4s. The left, right and forward segments were tested in a driving simulator with eight highway scenarios: two with forward warnings (decelerate), two with left warnings (abort lane change), two with forward recommendation (accelerate), one with left recommendation (change lane to the left), one with right recommendation (change lane to the right). The experiment showed an effect for the lane change tasks, but not for the longitudinal tasks (warning and recommendations in the front). The red warnings were experienced as "very prohibitive, limiting and enforcing, while [the green] recommendations were rated as permissive, expanding and relenting". Furthermore, the authors assume that the ambient lights may have been perceived as "recommendations to do something" rather than a "signal to stop an action" [DKS16].

The presented works commonly use lights to realize symbols using different colors or dedicated LEDs and shapes. What is missing is a light pattern that is purposely designed to address peripheral vision and thereby inform a driver unobtrusively while the situation is not critical but get the attention when the gap is too close to initiate an intended overtaking maneuver.

4.5.2 Approach

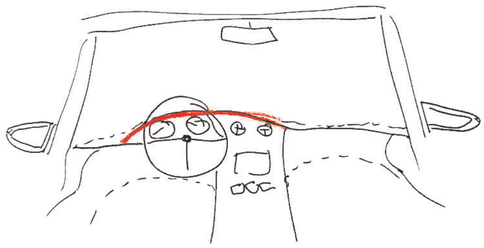
We organized a design workshop consisting of two sessions and invited five drivers (one female) with expertise in developing human-computer interfaces, two of them with a focus on light patterns.

In the first session, we explained our scenario and asked the participants to sketch their ideas for different light patterns. Between sessions, we grouped the results and implemented seven patterns for our scenario. In the second session, two days later, participants used a driving simulator to experience the different light patterns. Afterwards, we discussed benefits, drawbacks and possible improvements of the proposed designs.

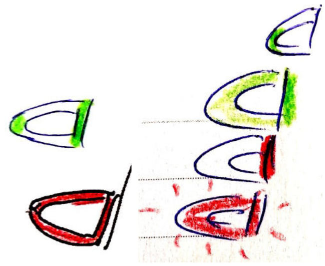
4.5.3 Sketching the Light Patterns

We explained the scenario and demonstrated light patterns using a strip of LEDs behind a semi-transparent foil. These light patterns did not react on any input and were just designed to demonstrate the capabilities of a single addressable LED strip, such as chasing lights with different colors, or a moving rainbow. To trigger ideas, we presented the following questions:

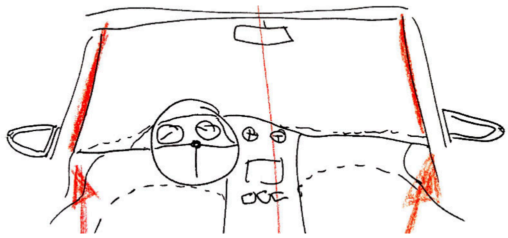
- Assuming a perfect assistant system (e.g., no sensor problem): How can a light display support the driver?
  - What if the driver correctly assesses the gap? (big enough, too small)
  - What if he or she does not? (leading to a collision, or traffic jam / not optimal flow of traffic)
- Assuming the system knows the drivers certainty of assessment: How to adapt the display?



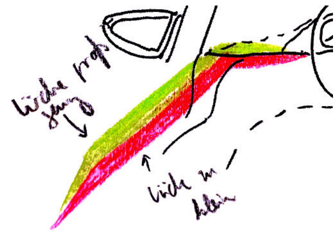
(a) Red warning in front.



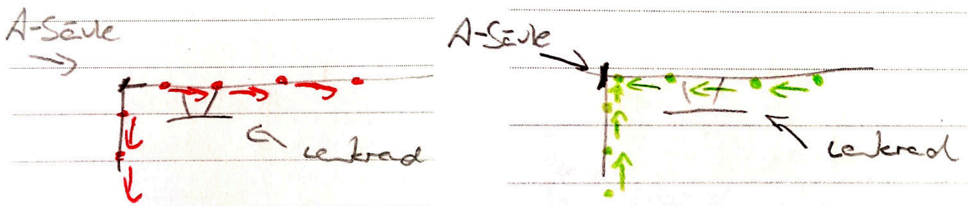
(b) Red warning and green recommendation in side-view mirrors.



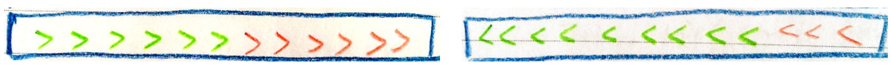
(c) Red warning in A-pillars.



(d) Red warning or green recommendation on the left door



(e) Red warning (moving away from the left corner) or green recommendation (moving to left corner)



(f) Moving pattern with gap representation: Recommendation by moving to the left with many green LEDs, warning by moving to the right with many red LEDs.

Figure 4.17: Examples sketches for discrete (a-d) and continuous (e-f) encodings.

We provided colored pens, sketches of the interior of a car and blank sheets, and asked the participants to sketch at least one idea. Afterwards, all sketches were collected and discussed in a plenum. This session took about 90min. Eleven distinct ideas emerged. Examples are shown in Figure 4.17.

4.5.3.1 Results

We summarize the common characteristics of these sketches in the following.

Locations

Most often, participants placed the lights at the sides: twice at the side-view mirrors (e.g., Figure 4.17(b)) and once at the upper part of the A-pillar (Figure 4.17(c)). Two light patterns were designed with the same width as the dashboard being active below the windscreen (e.g., Figure 4.17(a)). Another two patterns are located at the front and the sides below the windows (e.g., Figure 4.17(e)). The locations for the remaining sketches were not defined in detail.

Colors

Every light pattern used the color red to indicate a gap that is not safe for changing lanes. A gap that is just big enough to initiate a lane change with caution is always indicated with yellow, or orange. However, this cautious distance class was only proposed twice, while one participant also proposed orange, but stressed that this class should for safety reasons not be used.

In all but one cases, green indicates a safe gap. Once, a sketched pattern uses green and red at the same time and directly maps the gap to the ratio of green and red lights: the smaller (and thus less safe) the gap, the more red lights.

Once, blue and turquoise were proposed as an alternative for displaying a safe gap. In the same idea, orange and purple were suggested as an alternative for red as warning colors. Blue was also suggested once as calming color if a drivers workload is too high. Further, colors that are not located between red, orange, and green, such as blue or white, could be used as a neutral color to indicate if the assistant system is active.

Temporal Behavior

We use the term "temporal behavior" to indicate how the light pattern changes over time. Most often (six times), the participants suggested switching between distinct colors, e.g., changing from green to red. Four times, blinking or pulsating was proposed to increase the saliency of the display to warn the driver. In all cases, this behavior was combined with a red color. In four cases, the design should use one or more moving lights:

- The pattern moves as fast as the approaching vehicle.
- One green light moves, if the driver is right and the gap is safe, three points move, if the driver is right and the gap is not safe.
- Multiple lights move from B-pillar and opposite A-pillar towards the A-pillar, if the gap is safe, or away from it if the gap is not.
- Multiple lights in the front move towards the lane, if the gap is big enough or away from the lane if not. The LEDs in the direction to the target lane are green. The number of LEDs, or width, of the green illuminated part of the display, correlates with the gap, the rest of the display is red.

Discrete and Continuous Encoding

The sketched light patterns can also be categorized into two classes: those with stepwise changes and constant location of the light, here referred to as “Discrete Patterns”, and those with continuously changing parameters like brightness, location of the cue, or color, here referred to as “Continuous Patterns”.

Discrete Patterns Some sketches for discrete light patterns are shown in Figure 4.17(a)-4.17(d). In each case, a red light indicates that a driver should not overtake. This light is either positioned on the left side or in front of the driver. If the gap is big enough, either the light is turned off, or green to indicate a safe distance.

Continuous Patterns In the second class, the temporal behavior should give further information about the car. For example, the lower two sketches in Figure 4.17(e)-4.17(f) show a design, where points wander from left to right, if a driver should stick to the left, or the other way round for the opposite recommendation. Further, the number of green points refers to gap size.

Different Designs When the System Knows the Drivers Assessment

Most designs did not distinguish between patterns for a driver who is aware of the situation and drivers who are not. However, one suggestion is to increase the salience of the display, if a driver mistakes an unsafe gap for a safe one, while the salience could be decreased if the driver is aware of the unsafe gap. Another participant describes how this can be accomplished: while the whole display is active if the driver is wrong, only a few light points indicate the situation, if the driver has the right estimate. Another idea is to deactivate the assistant system if the driver is overloaded or too uncertain about what to do. It could be replaced by a calming blue light with LEDs moving away from the lane and thus recommending not to overtake.

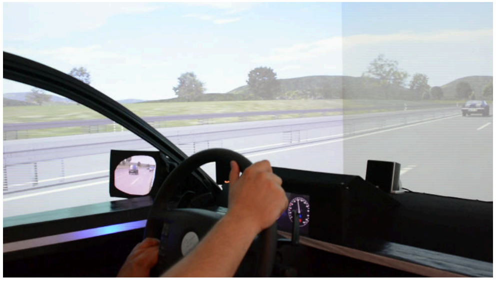
Further Suggestions

The participants also gave further recommendations while sketching the designs or when discussing them afterwards: One person was concerned about legal issues if the system was indicating safe distance when it was actually not safe to overtake. Two participants suggested indicating if the system is active or not. One suggestion is to activate the system only if an intention to overtake is sensed, e.g., if the indicator is activated or a slower car is recognized in front. Further, abrupt color changes should be avoided.

(a) Red at the door

(b) Moving red and green dots

(c) All LEDs changing



(d) Moving dot at the door

(e) Filling up the lights

(f) Fading the lights

Figure 4.18: Simulator with lights, indicating if the distance to an approaching rear car is safe.

4.5.4 Implemented Designs

After analyzing the proposed designs, we implemented three light patterns based on the sketches and four that were not proposed to stimulate further discussions. In every design, we defined a TTC of less than 2s as not safe. The resulting designs are described in the following.

Red or green at the door

This implementation represents the most common choice of color and behavior: the lights at the door (between A- and B-pillar) turn red if the gap is not safe (Figure 4.18(a)). If there is no car within a safety-relevant distance, the display stays green. In our implementation, the “safety-relevant distance” is defined as a time gap of two seconds between the approaching rear vehicle and the ego car.

Red at the door

This is a modification of the first pattern: A safe distance is not displayed, only the red warning is triggered (Figure 4.18(a)).

Moving red and green dots in front

This is the most complex sketched design. Green and red lights move towards the left, if the leftward gap is safe, or move to the right, if not (Figure 4.18(b)). At the same time, the width of the green part of the display, i.e., the number of green LEDs, correlates with the gap size, while the rest of the display stays red. This pattern is an instance of a continuous pattern with lights that move at a constant speed. Besides the general feedback for this concept, we were interested to see, if this pattern was too complex to be understood intuitively.

All LEDs changing from red to green

To check, if the color-change has to be discrete, as suggested by the participants, we implemented a light pattern, where all LEDs changed from green to red in a continuous way, the closer a car gets (Figure 4.18(c)). We expected negative feedback for this pattern. However, an example of a continuous color change could also foster discussions and generate new ideas. The linear color hue gradient ranges from green at 10s time gap via orange to red at 2s and stays red until the approaching vehicle has passed.

Moving dot at the door

This pattern represents the ideas with moving lights and is further inspired by [LCR11] and [MLHB14]. The ALD shows a light dot that maps its position to the TTC to the approaching car: it moved from the B-pillar, behind the driver towards the A-pillar, the closer the other car approaches. However, while all participants suggested using colors between red and green to discretely indicate a distance class, we used blue as color (Figure 4.18(d)). Using this example, we wanted to discuss if the color is needed to help in assessing the gap.

Filling up the lights at the door

Analogous to the moving light dot, we implemented a design, in which the lights filled up from behind the driver to the position of the moving light (Figure 4.18(e)). In this way, the display would get more salient, the closer the other car gets. This pattern is another alternative to the usual designs suggested by the participants.

Fading the lights at the door

This design is the inverted version of "filling up the lights at the door" (Figure 4.18(f)). In contrast to that design, an approaching rear car is represented by "missing light", in a shadow metaphor. The participants did not propose this concept, but we added it to generate new ideas.

4.5.5 Discussing the Patterns

In the second part of our workshop, two days after the first part, we explained the scenario once more to the participants. Afterwards, we introduced them to the driving simulator. During the session, each participant did a few overtaking maneuvers with at least one design implementation in our simulator equipped with a light display. The remaining people were asked to observe and take notes for later discussions. While this part of the session was rather unstructured, it led to a relaxed atmosphere that sparked discussions. In total, every participant tried at least one design. We then discussed possible improvements or alternatives, and asked if the implemented designs fulfilled their expectations. Further, we asked for the participants' concerns regarding light in the car and if they could see differences to other lane change decision aid systems, such as blind spot warning systems. This session took about 120min.

Possible Improvements and Alternatives per Pattern

Red at the door and *Red or green at the door* were considered as very close to common blind-spot notification systems. Participants suggested removing the safe state or make it less salient and only activate it if a driver intends to change lane. Furthermore, a green light was perceived as a recommendation and should thus be used with caution.

Participants did not like continuously changing colors in *All LEDs changing from red to green* since this makes it hard to distinguish between "safe" and "risky" distances. For example, it was not clear, what yellow would indicate. Further, the participants stated that the "phases" of each color were too short and that there was "too much red". Activating the display much earlier would be one possible solution for this problem.

Moving red and green dots in front was perceived as too bright with too many active LEDs. Further, it was hard to find the difference between safe and risky lane change. Also, while there is still a gap, the whole display should be red, if the TTC is below two seconds. A light pattern with multiple green or red light dots moving towards or away from the A-pillar was suggested as an alternative.

The benefit of the *moving dot* is that it is possible to encode multiple cars. The benefit against common blind-spot systems is the given spatial information and relative speed of the other cars. However, it can be confusing whether the encoded information is TTC, time gap or distance gap. Also, the border between "safe" and "risky" gaps was still reported to be hard to find.

Filling up and *fading the lights* were called "loading bar" by the participants and share the benefits and drawbacks with the moving dot apart from the possibility to encode multiple cars. Therefore, the moving dot pattern was preferred.

Things to Consider

We asked the experts, what we need to consider in general. In their opinion, the light display has to be able to adapt its brightness. It shall not blind a driver, but also be visible when driving on a sunny day. Further, the encoded information should be clear. For example, a driver should know, if the light pattern encodes an abstract warning, a TTC, or the distance gap in meters.

Regarding peripheral perceptibility, the participants stated that all encodings could be recognized in the periphery, but some could not be processed without focusing on them. This may not be a problem, however, if the information is not a warning but only needed "on demand". Another remark is that encodings that are only visible in the front, might not be seen while preparing a lane change and thus focusing on the side-view mirror and the traffic behind. Hence, the pattern should be straightforward, such as a red warning, or not only located in the front.

Some light patterns were not very distinct from blind-spot warnings and in the opinion of the experts do not need to be, as the scenario is the same. However, adding a spatial dimension to the light display gives the possibility to encode information independently from color. As some patterns suggest, it is also possible to encode another kind of information. For instance, "give an overview on rear traffic situation" compared to "warn about close cars".

Another topic which came up during the discussion was the need for smooth transitions. The experts stated that all light patterns, even with distinct classes of colors, have to avoid blinking or discrete transitions. Further, the display should not change while the driver is deciding on an action. When asked which pattern to compare against a discrete warning, the participants suggested using the moving dot encoding with an additional color encoding of the TTC.

4.5.6 Summary

We identified several possible designs to indicate the distance to an approaching rear car using ambient light. After defining a scenario, we let participants sketch their design ideas. We implemented seven designs based on their and our ideas, and let the participants experience them. Afterwards, we discussed the designs' characteristics and further benefits and drawbacks of using ALDs for this kind of assistant system.

We learned that we could assist a driver using different kinds of light patterns. State-of-the-art systems use distinct colors to represent warning classes which were also designed in our workshop. However, we also saw light patterns with a continuous encoding of TTC or time gap. These patterns used colors from green to red to show the criticality, but occasionally also a temporal or spatial dimension to encode the information either via speed of moving light dots, via the position of light dots or the width of active LEDs.

4.6 Further Light Displays in Literature

This section summarizes related works that use light displays to assist drivers and are have not been discussed in this chapter so far. These works were also summarized in our published analysis of systems that implement light patterns for ALDs in [LHB16b].

4.6.1 Visualizing Other Traffic Participants and Obstacles

In contrast to blind spot warnings during a lane change, displays in this category warn, e.g., about objects in the forward blind spot or highlight pedestrians with poor visibility. Light patterns in this category are most often located in the direction of the other object.

Yu et al. [YKG07] propose a multimodal driving assistant which gives feedback about objects in blind spot areas. They equipped a toy car with a size of approximately 60x85cm with distance sensors in each corner and added a 5x8 LED matrix, an audible buzzer and two tactile vibrators as indicators. The LED generate “mild indications” at a distance of .5 to 1 car. The signal escalates by adding vibration and sound if an object is closer than .5 car lengths. However, it is not revealed, how the LED indications are designed.

Mahlke et al. [MRS+07] analyzed combinations of sensors and displays for night vision enhancement. One of the six evaluated displays was an LED-strip between the steering wheel and the windscreen. A light would turn on in the direction of the recognized pedestrian. Heuristic evaluation and a field experiment were carried out to test the prototypes. The authors conclude that the LED prototype showed the best results. The most important reasons for that were that “the system is very easy to learn”, “hazardous events are detected and signaled automatically” and “the unobtrusive location of the system avoids blocking central parts of the visual field” [MRS+07].

Fricke et al. [FT09] compared designs for a forward collision warning system in a driving simulator study. One of the designs included a light display that was based on the approach of Mahlke et al. [MRS+07]. However, the light pattern is realized as a red light flashing at 10Hz in the direction of the other traffic participant. The authors found that multimodal warnings led to faster response times. They assume that visual cues help to decrease reaction times. Also, they suggest that the exact spatial information “may not be as helpful as expected because people might not be able to process it in a hazardous situation that calls for a fast response” [FT09].

Borges et al. [BZT13] integrated a system into a forklift to warn about pedestrians. Their prototype uses off-board cameras to track pedestrians and trigger collision warnings: an orange and a green LED are mounted in every top corner of the interior of the forklift. Depending on the direction towards a pedestrian, the corresponding orange LED flashes. The frequency is inversely proportional to the distance to the closest pedestrian. Each green LED is located below each orange LED and is active whenever information from off-board cameras are in range. The system was tested at two real industrial sites for four months. The authors conclude that “the system can be useful as an auxiliary safety measure, successfully alerting drivers of nearby pedestrians with a practical error rate” [BZT13].

Pfromm et al. [PCB13] developed a ° light display. LED strips are located in front of the driver, below the windscreen, on the sides, and behind the rear seats. The idea is to direct the driver’s view towards traffic objects in a high number of use cases. These objects are “projected” on the light display. Thus, the light encodes the direction via the location of the light source and the distance via the number of activated LEDs. The display was tested in a driving simulator in four scenarios that showed a car (a) standing behind a road bend, (b) crossing a street from the left (ignoring rules), (c) crossing the street from the right, and (d) approaching from the front, while the driver wants to turn left. On average, the participants needed less time to focus on the object. However, the results varied widely, and the significance was not tested. Furthermore, the ratings showed that the display is perceived as “simple, safety improving, manageable but partly distracting” [PCB13]. The authors also conclude that “most drivers intuitively understood the content of information” [PCB13].

Meschtscherjakov et al. [MWB15] designed a forward blind spot information system. A 3x18 LED matrix was attached to the A-pillar of a car to inform about objects which are covered by the A-pillar from the driver’s perspective. Two designs were implemented in a real car. The *bottom-top* pattern indicates the distance by increasing the number of active LEDs the closer an object gets, starting at the bottom of the matrix, while also changing the color from green to red. The *middle-out* pattern starts in the middle of the matrix and uses the number of LEDs in red color to indicate the distance. Each column of the matrix is used to indicate the direction to the object. Hence, only one column is active if there is only one object. The designs were compared in a small user study with five drivers. The results indicate that both encodings are intuitive. Further, the authors claim that the distance was easier to perceive with the *bottom-top* design. They further propose that the brightness should adapt to the ambient lighting conditions, transitions should be smoother and flickering should be avoided in the future.

4.6.2 Displaying Speed Recommendations

Apart from traffic signs, speed recommendations are usually given visually. Either as part of the navigation system that may also warn about speeding acoustically or on brought in devices. The designed light cues are always triggered in front of the driver.

In order to support a safer and less fuel consuming driving behavior, Laquai et al. [LCR11] developed a light display which gives feedback about a needed deceleration. Each display consists of modules which can show one color at a time. The first display, consisting of two modules, is located beside the steering wheel. Three deceleration strategies are encoded: *green* for coasting, *yellow* for light braking and *red* for strong braking. The transition between these three states was linearly interpolated with a time of 1s. Furthermore, distance and reason for the needed deceleration are given as symbols in the dashboard. The first experiment revealed, amongst others, that the color *green* was not intuitive, as it was understood as "Everything OK". The results were taken into account for the next iteration of the light display, consisting of 18 modules: it does not point directly to the driver, is diffuse, and located below the windscreen. After 20 participants calibrated the colors to fit to their perception, the colors were changed to yellow (RGB(100%, 100%, 0)), orange (RGB(100%, 54.9%, 0)) and red (RGB(100%, 0, 0)) with a transition time of 2s. The width of the light, i.e., the number of active LEDs, increases linearly from 3 LEDs in the middle at a distance of 1000m to full width of 90 LEDs (1.6m) at 0m. Additionally, a second concept using the same colors and classes was implemented. Its metaphor is *moving lights while driving through a tunnel*. In order to achieve this effect, two diagonal lines of 36 LEDs were attached to the front lid pointing forwards. A light dot consists of three LEDs and moves towards the driver if the driving speed is too slow. Analogically, it moves away from the driver if the speed is too fast. The speed of the dots depends on the difference between the current and suggested speed: the higher it is, the faster the light. In both designs, the distance and reason for the needed deceleration are given in a heads-up display. Both designs were compared against a baseline condition without assistance in a driving simulator study. The authors found that participants decelerated earlier and more constant.

Jahan et al. [JHW13] propose an interface consisting of three LEDs which indicates if a driver is below or above a target speed. In addition, an LCD screen displays the current location, speed and recommended speed. A green LED is active, if the current speed is equal or below the target. A red LED blinks faster the more the current speed is above the recommended one. Further, a blue LED is activated every time the car enters a new speed zone. The location of the display is not reported. The system has been tested on a test track. However, no user experience or driving performance related experiments were conducted.

In order to help drivers keeping the desired speed, Meschtscherjakov et al. [MDRT15] created *ChaseLight*. In their system, 190 LEDs are attached to the upper part of both A-pillars. Three designs with moving green light dots were implemented and tested in a driving simulator. The first pattern uses a "chasing lights" pattern with constant speed to indicate the recommended driving speed. The second design adapts the speed of the moving light dots: the faster the car, the faster the dots. The third pattern adapts the dots' speed based on the current and target speed: the closer the car's speed is to the target, the slower the dots. If the car is moving faster than the target speed, the dots are moving towards the driver. If the car is slower, the dots move away. If the car's speed is close to the target, the dots do not move. Suitable parameters for the designs were found in informal explorations in a driving simulator. The final patterns were compared in a driving simulator study. The results showed that the third pattern, which adapted the speed to the target, outperformed the other patterns regarding speed keeping, perceived usefulness, and subjective workload.

4.6.3 Directing and Visualizing Gaze

Directing a driver's gaze is not a commercially available assistance function. Two papers reported how to direct the driver's gaze [PDBB13] or visualize the front seat passenger's gaze to help him or her to assist the driver [TWD+15].

In the prototype of Pomarjanschi et al. [PDBB13], an LED strip is attached horizontally above and below the windscreen. The color of each LED was red. On the top display, two LEDs flashed in the direction where the driver's gaze should be directed to, i.e., the most right or most left two LEDs. On the bottom display, all LEDs between the last gaze and the end of the display were turned on and off rapidly in a way which created a "chasing lights" pattern towards the left or the right. The gaze behavior with and without the system was analyzed in a driving simulator experiment. The authors were able to find that the light patterns directed the driver's gaze to the desired direction without drawing it towards the LEDs.

Trösterer et al. [TWD+15] developed a light display which visualizes where the front-seat passenger is looking at. The used display consists of 216 LEDs below the windscreen. Five blue LEDs interpolate a light point which is moved to be in the driver's line of sight towards the point where the passenger is looking at. In a driving simulator experiment, the system was tested against an alternative implementation, where a dot in the simulated environment represents the passenger's focus point. According to the authors, most results indicate that the dot outperforms the LED-based visualization. It is assumed that the reason for this is that the LEDs are less accurate and that the passenger cannot verify if the light cue points into the intended direction. On the other hand, LEDs were reported to be easier to ignore and thus less distracting and easier to perceive. Hence, a light-based visualization might be more useful whenever accuracy is not as important.

4.6.4 Displaying the Vehicle's State

Two works focused on displaying the vehicle's state using ambient light. One system is designed to display information about the climate control system [Suk13], while the other gives feedback on current energy consumption and battery state of an electric vehicle [LLKB14].

Hyeon-Jeong Suk [Suk13] designed a light interface which displays relevant information for in-car climate control. In the first step towards this goal, a workshop was done to match input measurements to color parameters, extract five scenarios and evaluate it based on how *interesting*, *informational* and *inspiring* the scenario would be from a user's perspective. In the resulting scenario, the colors were matched to the temperature in the car and the blow level of the climate control. In the second step, twelve climate situations, consisting of four blow levels and three temperature levels, were implemented. In a user test, these situations were matched to one of 45 predefined color stimuli by 36 participants. After analyzing the results, a design was proposed: it uses the colors from blue via white to red to indicate the in-car temperature. Further, the saturation indicates the blow level: the more vivid, the higher the blow level. However, the design was not implemented.

With *Heartbeat*, Loehmann et al. [LLKB14] developed a multimodal information system which displays the power consumption and battery state of an electric vehicle via light and vibration. The authors described how they used *experience stories* throughout each design stage. In short, the design should resemble the heartbeat of a runner, with a fast beating heart when most active, and the need for breaks when the energy is low. An *experience prototype* which only includes aspects that are needed to test the experience was realized: a sphere above the central console and an acrylic glass below. The sphere can vibrate when touched to resemble the heartbeat, while both can be illuminated. The acrylic glass indicates the battery state via the width of its stream of light. Both displays glow in blue because that color represented "power and energy" [LLKB14]. Experts were interviewed, and three small user studies were conducted to receive early feedback using this prototype without a driving simulator. After analyzing the results, a high-fidelity prototype was integrated into a car-mockup in a driving simulator. A context-creating story was created to test the display in a driving simulator study. The results indicate that the user experience was positive.

4.7 Summary

At the beginning of this chapter, we discuss different locations and several applications for ALDs in the vehicle. In addition, we give an overview of in-vehicle light displays in related works. In the following, we will summarize how this chapter contributes to our research questions.

4.7.1 Contributions to RQ1 – Investigating Parameters for Ambient Light

Overall, the discussed automotive works and our studies support and expand the previous guidelines for ambient light displays.

We investigated the location of the display as one of the parameters of an ALD. In summary, drivers prefer to have the display close to a piece of information that is highlighted by the display. This preference is in line with the preferred placements in the other studies of this chapter. The light patterns for the navigation assistance and lane change decision aid system showed that spatial information could be encoded by changing the location of the light cue. Furthermore, the size of the light source, i.e., the number of active LEDs, is commonly used in related works to indicate a distance.

Another parameter that was similarly used throughout the experiments is the color of the display. Participants proposed green and red colors to encode the safety level which is in line with the guidelines presented in Section 3.2 and the discussed related works. We also learned that white, blue, and purple could be used as neutral colors to inform drivers.

The temporal behavior has to be defined with caution. Participants repeatedly pointed out that blinking and pulsing patterns should only be used to get the driver's attention. Also, in the discussed related works, we observed that increasing criticality levels are commonly encoded by switching to red color and increasing the speed of blinking or pulsing patterns. Further, transitions between states (e.g., color or brightness changes) need to be smooth to avoid blinking. Related works also proposed moving lights to indicate the current target speed.

Throughout the studies, participants were concerned that the light patterns might blind drivers when they are too bright or not be perceived because they are too dim and thus need to be adapted to the ambient light level. Also, bright lights may distract passengers and other traffic participants. Therefore, the information encoding should not rely on the brightness level.

4.7.2 Contributions to RQ2 – Displaying Important Information Effectively

Our literature review indicates that light displays may impact driving performance positively. Also, while the studies in this chapter focused on exploring designs and thus RQ1, some results contribute towards RQ2. For example, we did not observe that drivers were distracted to an extent that it would affect their performance negatively, which was one of the biggest concerns of drivers in the interviews. In contrast, drivers performed better with our ALD based navigation system, compared to a GUI based system. We will focus more on this research question in the following chapters.

4.7.3 Contributions to RQ3 – Effects of ALDs on Gaze Behavior

We only looked into gaze behavior in the NaviLight experiment (see Section 4.2). However, the results indicate that drivers do glance less often and shorter away from the center while their performance indicates that they still received the relevant information.

5 ALDs for Lane Change Decisions

As motivated in Section 4.5.1, changing lanes is a complex task [Hen10]. As accident statistics show, misperceptions or mistakes during this can lead to severe accidents: 22% of accidents with injuries on German nonurban roads were caused by insufficient safety clearance (17%) or errors during overtaking maneuvers (5%). 41% of the latter accidents were caused by ignoring approaching rear cars on the target lane, not indicating the maneuver or overtaking in unclear traffic situations [Sta18a]. Helping the driver to assess the relative speed and gaps towards the surrounding cars may help to reduce the chance of misinterpretation and thus reduce the number of accidents. Still, the assistance system needs to use a modality that does not further disturb the driver or go unnoticed. Therefore, our goal is to develop a display that continuously informs the driver of the vehicle's and the environment's state without distracting him or her.

As discussed in Section 3.1, we argue that using an ALD can help to avoid increasing mental workload because it addresses peripheral vision, a cognitive resource that may be less loaded than foveal vision during the preparation for a lane change. Also, based on our previous work, we can argue that an ALD may be perceived as less distracting and thus has a higher chance to not distract drivers from receiving other critical information.

In this chapter, we present the results of four driving simulator experiments evaluating ALDs to support drivers during lane changes. We use this scenario to investigate RQ2 and RQ3 of this dissertation. The first experiment compares two light patterns against baseline driving without assistance. Both displays are based on our previous results (e.g., Section 4.5) and the ISO 17387 standard [ISO08]. We were interested in how these first implementations affect driving performance (RQ2). We learned from the results of the first experiments and ran a second experiment in which compared two versions of a refined ALD against baseline driving. Both displays start earlier to display the gap to the rear left vehicle. Further, one of them adapts to a model of the driver's uncertainty and therefore a part of the driver's state. After we observed some indications that an ALD can improve driving performance in a controlled scenario, we conducted the third experiment, focusing on driver and gaze behavior in more natural lane change situations. In a fourth experiment, we further investigated gaze behavior (RQ3), focusing especially on the difference to a comparable display that requires foveal vision. The primary objective of the research within this chapter is to compare the effect of ambient light and focal icons on driving performance (RQ2) and gaze behavior (RQ3).

5.1 Discrete or Continuous Encoding of the Gap

This section presents our work on an LCDAS with a driving simulator experiment comparing a discrete and a continuous pattern. Until this chapter, our results indicated that an LCDAS should be implemented by encoding safety-levels with a traffic light metaphor in the direction of the information or hazard. However, it is not clear if the gap to the

(a) Discrete pattern with fixed light in the front left corner.

(b) Continuous pattern with moving light along the left side.

Figure 5.1: Snapshots of the discrete and continuous light pattern. Both show an approaching rear left vehicle within warning range.

approaching rear left car should also be encoded via the location of the cue (see Section 4.5).

The goal of this work is to investigate which way to implement the ALD for an LCDAS leads to the better driving performance and if using our ALD reduces the number of risky overtaking decisions compared to baseline driving (RQ2). We hypothesized that the light pattern with moving cues and slow color transitions, called continuous light pattern, will be less obtrusive, but may not be noticed as often due to being so. The results are also published in [LMHB15]. This section extends on the publication by adding more discussion on the results per time gap classes.

5.1.1 Light Pattern Designs

One of the main challenges lies in creating a display that is both unobtrusive enough not to distract the driver, and is salient enough to inform the driver of the current situation. We realized two designs that display the TTC to an approaching rear left vehicle (TTC_{rear}) based on the feedback of the design workshop (see Section 4.5). The first pattern uses two colors and three discrete states (Figures 5.1(a) and 5.2). The second pattern continuously encodes TTC using the spatial location of the light and a color gradient ranging from amber to red (Figures 5.1(b) and 5.3). We describe both patterns in the following.

5.1.1.1 Discrete Light Pattern

The discrete light pattern uses one color per distance class as shown in Figure 5.2. It consists of four LEDs in the front left corner with a total width of 6.67cm as shown in Figure 5.1(a). It is based on previous designs with discrete color changes and related

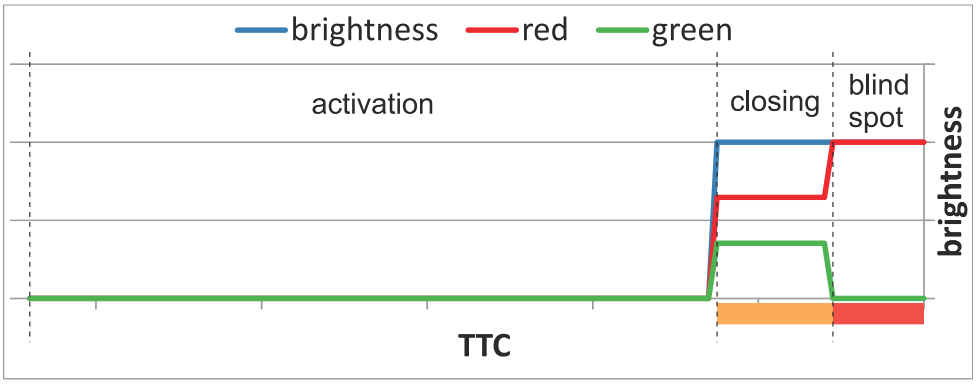


Figure 5.2: The ratio of red and green light in proportion to TTC (decreasing from left to right) for the discrete light pattern. If a car is within warning *distance, the light will turn amber. If it is within* blind spot *range or closer, it will turn red. If the driver sets the indicator while a car is within* blind spot *or closer, the display will blink three times at full brightness and stay at full brightness afterward.*

to common warning systems, such as Audi's Side Assist, as discussed by Bartels et al. [BSBS09]. We derived the definitions for the warning states from ISO 17387 [ISO08].

In line with the ISO standard, the light will warn about a vehicle when it is closer than a threshold of $\theta_{warn} = 2.5s$ for a speed-difference of up to $10m/s$ and $\theta_{warn} = 3s$ for a difference of up to $15m/s$ [ISO08]. The color for the warning is amber with an RGB value of 43.1% for red, 24.5% for green, and 0% for blue, or "110, 60, 0" in the range from 0 to 255. Once the car is below the blind-spot distance threshold, which is defined as $\theta_{bs} = 3m$ [ISO08], the light switches to red (RGB: 170, 0, 0). If the driver sets the indicator while a faster car is within blind-spot distance on the corresponding side, the light will blink red for three times at full brightness (RGB: 255, 0, 0) with a speed of 20Hz and stay bright red afterward.

5.1.1.2 Continuous Light Pattern

The continuous light pattern is based on the moving dot pattern of the previous workshop (see Section 4.5.4) and represents the idea to encode information continuously. As proposed by the participants, we did not only encode the TTC via the position of the dot but also via the color. Figure 5.1(b) is a snapshot of the light pattern. The activation threshold for our display is derived from ISO 17387 and defined as $\theta_{act} = 7.5s$ TTC or $\theta_{act} = 30m$ distance, depending on the relative speed [ISO08]. The light dot is closer to the A-pillar, the closer the other car gets until the car is within blind-spot distance. If we set the A-pillar location as 1 and the B-pillar location as 0, we can define the position of the light dot as:

$$p(ttc) = \begin{cases} \dfrac{ttc - \theta_{bs}}{\theta_{act} - \theta_{bs}}, & \text{if } \theta_{act} \geq ttc > \theta_{bs} \\ 1, & \text{if } ttc \leq \theta_{bs} \end{cases}$$

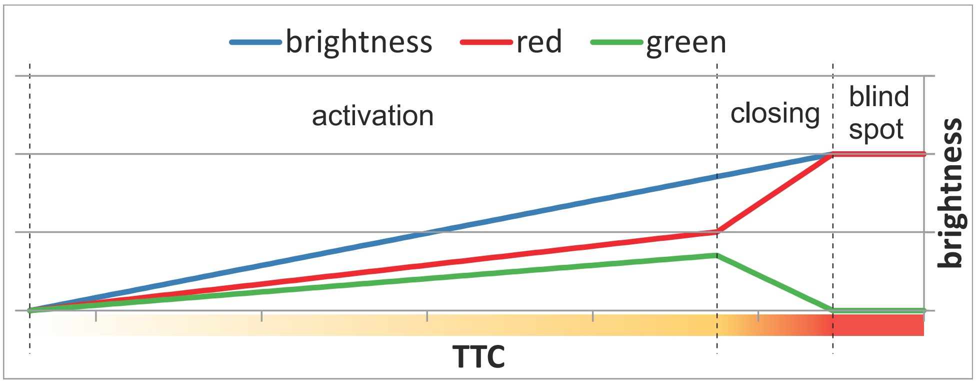


Figure 5.3: The ratio of red and green light in proportion to TTC (decreasing from left to right) for the continuous light pattern. The brightness increases linearly until the car is within blind spot *range. While the ratio of red and green is stable as long as a car is within* activation *range, the red component of the color will increase until only red is left if a car is within* closing *range. If the driver sets the indicator, the lights will be twice as red.*

The color of the light dot is also changing continuously as a function of TTC. As shown in Figure 5.3, the pattern starts with a dark amber at θ_{act}, hitting the same amber as in the discrete pattern at θ_{warn} and linearly turns into the same red as in the discrete pattern at θ_{bs}. This color change per TTC can be defined as follows:

$$
\begin{aligned}
g(ttc) &= 60 \cdot \begin{cases} 1 - \dfrac{ttc - \theta_{warn}}{\theta_{act} - \theta_{warn}}, & \text{if } \theta_{act} \geq ttc \geq \theta_{warn} \\ \dfrac{ttc - \theta_{warn}}{\theta_{act} - \theta_{warn}}, & \text{if } ttc < \theta_{warn} \end{cases} \\
r(ttc) &= -g(ttc) + 170 \cdot \begin{cases} 1 - \dfrac{ttc - \theta_{bs}}{\theta_{act} - \theta_{bs}}, & \text{if } \theta_{act} \geq ttc > \theta_{bs} \\ 1, & \text{if } ttc \leq \theta_{bs} \end{cases} \\
r'(ttc) &= \begin{cases} 2 \cdot r(x) & \text{if the indicator is set} \\ r(x) & \text{if the indicator is not set} \end{cases} \\
rgb(ttc) &= \begin{pmatrix} r'(ttc) \\ g(ttc) \\ 0 \end{pmatrix}
\end{aligned}
$$

This way, the maximum value for red is 170, and the one for green is 60 out of a range from 0-255 per color. If the driver sets the indicator, the red component is doubled to stronger highlight the danger of the current distance. For each LED within a radius of 1.5 LEDs around the calculated location and with the index (i) of the 43 LED starting at zero, its color is defined as follows:

$$
rgb_i(ttc) = rgb(ttc) - (i - p(ttc) \cdot 42) \cdot \begin{cases} rgb(ttc)/1.5, & \text{if } i < p(ttc) \cdot 42 \\ -rgb(ttc)/1.5, & \text{if } i \geq p(ttc) \cdot 42 \end{cases}
$$

5.1.2 Experiment

We implemented a lane change scenario with different gaps to a faster rear car and a slower car in front as sketched in Figure 5.4 for this experiment. The driver has to slow down, which may prohibit an optimal traffic flow or to overtake and risk interfering with the approaching rear car on the target lane.

To investigate if our light patterns help a driver in making better decisions, we set up a driving simulator experiment and measured the ratio of safe maneuvers and the number of missed overtaking opportunities per condition. We conducted post-hoc interviews to receive qualitative feedback and ideas for improvement.

In the context of this experiment, we define the requirements for a safe maneuver (R_1 and R_2) and a missed opportunity (R_3) as follows:

R_1 *Safety clearance to the front car was maintained.* We consider the distance to be safe, if $d_{front} \geq 50m$ when the indicator was set, or braking was started.

R_2 The lane was changed, and the *safety clearance to the car behind was maintained.* We consider the distance to be safe if $d_{rear} \geq speed_{rear} \cdot 2s$ at the start of the maneuver.

R_3 The lane was not changed, and *braking was necessary.* To overtake the leading car without accelerating at a speed difference of $30km/h$, it takes TTC_{front} seconds to get close to the car, $0.96s$ to overtake it and another $6s$ until the distance to the slower car is safe again. Therefore, a braking maneuver is unnecessary if $TTC_{rear} > 6.96s + TTC_{front}$, since it hinders an optimal flow of traffic.

We implemented the discrete pattern based on timings from the ISO standard. Hence, we expect it to help a driver to perform better than without assistance. Further, we assume that the continuous pattern will lead to better decisions as it starts to give information earlier. Third, we expect that using any assistance results in less cognitive workload. Hence, we hypothesize the following:

H_1**)** Using any light pattern will increase the number of safe maneuvers and reduce the number of missed opportunities compared to not using assistance.

H_2**)** Using the continuous pattern will increase the number of safe maneuvers and reduce the number of missed opportunities compared to the discrete pattern because the information is displayed earlier.

H_3**)** The cognitive load will be highest without assistance because the driver is not assisted. It will be lowest when using the continuous pattern because the assistance addresses a less used cognitive resource and is unobtrusive enough to not distract the driver.

We measured cognitive load with Raw TLX (RTLX), which is a NASA TLX without weights [Har06]. We were also interested in differences between the light patterns and therefore analyzed *intuitiveness*, *visibility*, *peripheral visibility* and *disturbance* for both light patterns. Each measure was explained to the participant and ranged from 0 (e.g., not intuitive) to 100 (e.g., very intuitive) in intervals of five, like the scales for each item in the RTLX. We also asked for additional feedback per measurement as well as general feedback for both designs.

5.1.2.1 Participants

19 drivers (7 female), with a mean age of 28.6 years (SD: 8.5) participated in our experiment. They possessed driving licenses for an average of 9.8 years (SD: 8.6) and drove $6,067km$ a year on average (SD: 6,772). Further, all but one participant had no experience with blind spot warnings or similar assistant systems.

5.1.2.2 Experiment Design

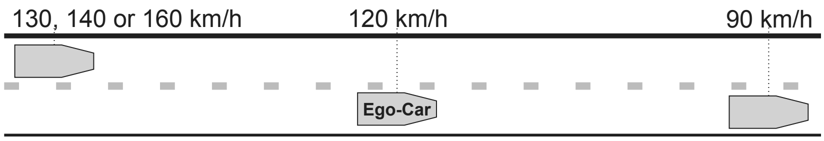
We designed the experiment as repeated measures with three conditions as the independent variable. In one condition, the discrete pattern for the light display (*Dsc*) changes its states, depending on the approaching rear left vehicle's TTC. In another condition, the continuous light pattern (*Cnt*) displays the TTC of the approaching rear left vehicle. The baseline condition (*Bsl*) does not have an active light pattern. We counterbalanced the order of conditions. Dependent variables are the ratio of "good" decisions, defined by R_1, R_2 and R_3, as well as the cognitive workload of a driver.

5.1.2.3 Procedure

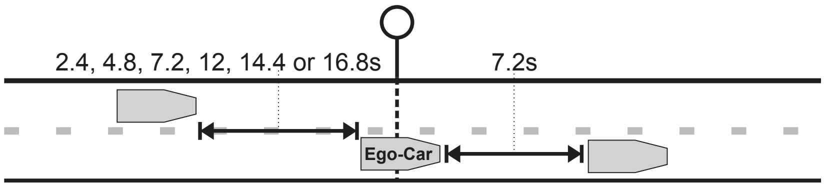
We started our study with an introduction by the experimenter and informed participants about their rights and privacy regulations. We further asked the participants to sign a written informed consent. Afterwards, we informed the drivers about the procedure and explained how to drive in the simulator. Before starting the driving tasks, we asked the participants to fill out the first part of the questionnaire, regarding demographic data.

We gave the drivers the opportunity to try out the driving simulator with three trials in each condition. If a driver did not feel confident, he or she could continue driving without other cars on the street, until the person felt ready to start. After the initial maneuvers, we started to log the data and initiated the driving tasks in a randomized order.

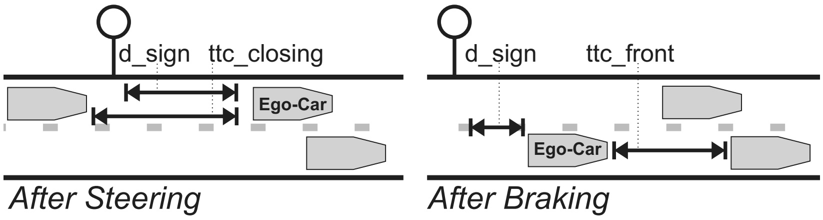
In every task, the participant's car accelerates automatically to $speed_{ego} = 120km/h$. We fixed this speed to ensure comparable results between the drivers. Once the own speed reaches 120km/h, the other cars appear. The participants drove 18 variations of the driving task in randomized order as depicted in Figure 5.4 and summarized in Table 5.1. The car in front drives at a speed of 90km/h and the rear left car at 130km/h, 140km/h or 160km/h. For each of these three variations, a standard street sign for *"end of no passing"* was positioned 7s away, where the rear left car will have a TTC to participant's car of 2.4s, 4.8s, 7.2s, 12s, 14.4s or 16.8s. We choose these TTCs because three of them are close enough to be within activation range, while three of them are far enough away



(a) Our scenario in the first stage of each driving task: the front car is driving at 90km/h, the rear car either at $speed_{rear}$ = 130, 140 or 160km/h and the ego-car is automatically accelerating to 120km/h.



(b) After 7s, the ego-car passes the sign. TTC_{front} is then $7.2s$. TTC_{rear} is one of $2.4s$, $4.8s$, $7.2s$, $12s$, $14.4s$ or $16.8s$ for each $speed_{rear}$.



(c) After the maneuver, the distance to the sign (d_{sign}), as well as TTC_{rear} or TTC_{front} are measured, depending on the decision of the driver.

Figure 5.4: Different stages of the driving task in our scenario. By varying the three levels of $speed_{rear}$ and six levels of TTC_{rear}, each participant drives in 18 variations of it.

to not be relevant by an LCDAS. The car in front was positioned to be at a time gap of 1.8s when the driver passes the sign to ensure quick responses. Once the driver reacts by either changing the lane or braking, the cars disappear. The next iteration will start after the driver is back to the right lane and a speed of 120km/h. The participants were instructed only to overtake after they passed the sign, and whenever it feels possible to overtake safely.

After each condition, the participants assessed their workload using the RTLX. Further, they rated *intuitiveness*, *visibility*, *peripheral visibility* and *disruptiveness* of the light pattern as described earlier. Furthermore, we conducted a semi-structured interview about the characteristics of the displays after each condition and a wrap-up discussion at the end. Each experiment took about 60 minutes.

Speed of the rear car	Expected value when passing the sign						
(any)	TTC (s)	2.4	4.8	7.2	12.0	14.4	16.8
	Dsc state	warn	-	-	-	-	-
	Cnt state	warn	active	active	-	-	-
130km/h (36.1m/s)	Gap (s)	0.2	0.4	0.6	0.9	1.1	1.3
	Distance (m)	7	13	20	33	40	47
	Risky?	yes	yes	yes	yes	yes	yes
140km/h (38.9m/s)	Gap (s)	0.3	0.7	1.0	1.7	2.1	2.4
	Distance (m)	13	27	40	67	80	93
	Risky?	yes	yes	yes	yes	-	-
160km/h (44.4m/s)	Gap (s)	0.6	1.2	1.8	3.0	3.6	4.2
	Distance (m)	27	53	80	133	160	187
	Risky?	yes	yes	yes	-	-	-

Table 5.1: Variations of the driving task. The participant's car is driving at 120km/h (33.3m/s), and the lead car 90km/h (25m/s). The scenario is set up in a way that the "end of overtaking prohibition" sign is placed at the spot at which the time gap to the lead vehicle is 1.8s if all speeds stay constant. Similarly, the initial position of the rear left car is set far enough away to reach one of the six TTCs defined in the table when the participant reaches the sign at the given speed. For the analysis, we consider a gap of less than 2s as risky (R_2).

	Baseline				Continuous				Discrete			
	M	SD	Mdn	IQR	M	SD	Mdn	IQR	M	SD	Mdn	IQR
!R1 ^{a}	4.5	5.5	3.0	6.0	5.2	5.3	3.0	4.5	6.3	5.5	3.5	9.0
!R2	4.4	2.7	5.0	4.0	4.8	2.6	5.0	2.8	5.2	2.8	5.5	4.0
!R3 ^{a*}	1.9	1.7	1.0	2.0	1.0	1.1	1.0	1.0	1.6	1.4	1.0	1.0
Safe *	**9.9**	4.8	10.0	5.5	8.8	4.6	10.0	6.0	**7.7**	5.0	8.0	7.0
Good *	**9.1**	3.9	10.0	4.0	8.4	4.2	10.0	5.5	**7.1**	4.3	8.0	6.5

Table 5.2: Means (M), medians (Mdn), standard deviations (SD), and inter-quartile ranges (IQR) for the number maneuvers per participant that violated a requirement ($!R_1$, $!R_2$, $!R_3$), or can be considered a safe ($R_1\&R_2$) or good ($R_1\&R_2\&R_3$) maneuver. Not normally distributed results are marked with ^{a}, statistically significant differences are marked with *.

5.1.3 Results

One-way within-subjects analyses of variance (ANOVA) were conducted to test if the different light patterns affected the number of good maneuvers. If significant effects were observed, we did post hoc comparisons using Tukey's tests with Holm corrections. The results for some measurements were not normally distributed and therefore tested with Friedman tests. In this case, post hoc comparisons were conducted using Wilcoxon signed rank tests with Holm correction. Effect sizes were calculated using Cohen's d and reported as d. Descriptive statistics are given in Table 5.2. We will discuss significant effects in the following.

5.1.3.1 Safe Maneuvers (R_1, R_2)

The number of maneuvers that resulted in risky gaps to the lead car (violation of R_1) had a median of 3 for *Bsl* and *Cnt* and one of 3.5 for *Dsc* and did not differ much ($p = .13$). Similarly, the number of maneuvers that resulted in an unsafe gap to the rear vehicle (violation of R_2) did not differ substantially ($p = .21$).

However, when taking R_1 and R_2 together, to define "safe" maneuvers, the number differs significantly ($p < .05$). Post-hoc comparisons showed that using the discrete pattern led to fewer safe maneuvers compared to baseline ($p < .01, d = .46$), while there was no significant effect between *Cnt* and the other conditions (both $p = .24$). This effect of the discrete pattern on baseline can also be described as a drop from deciding for a safe decision in 55% of the cases to 43% on average per participant and contradicts H_1 for *Dsc* The results also do not support H_2.

5.1.3.2 Missed Opportunities (R_3)

As shown in Table 5.2, we observed a significant effect of the used light pattern on the number of missed opportunities to overtake ($p < .05$). However, the Wilcoxon tests showed no significant differences between the patterns on a $p < .05$ level. The number of missed opportunities thus does not support H_1 or H_2.

5.1.3.3 Good Maneuvers (R_1 - R_3)

For further insight, we analyzed the number of "good" maneuvers which are defined by a combination of R_1-R_3. Concerning our hypotheses, we expect that using light, especially the continuous one, would lead to better maneuvers. As shown in Table 5.2, this is not supported. The ANOVA showed that there is a significant difference between the conditions ($p < .05$). In line with the results for safe maneuvers, post-hoc comparisons showed that using *Dsc* led to fewer good maneuvers ($p < .01, d = .49$), while we observed no other effects.

5.1.3.4 Mental Workload (H_3)

All conditions received low RTLX scores as shown in Figure 5.5. The results are not normally distributed. The median values are 17.5 for *Bsl* (IQR: 15.4), 16.7 for *Cnt* (IQR: 13.3), and 18.3 for *Dsc* (IQR: 17.9). A Friedman test did not reveal significant effects ($p = .77$). Therefore, our hypothesis regarding reduced cognitive load is not supported (H_3).

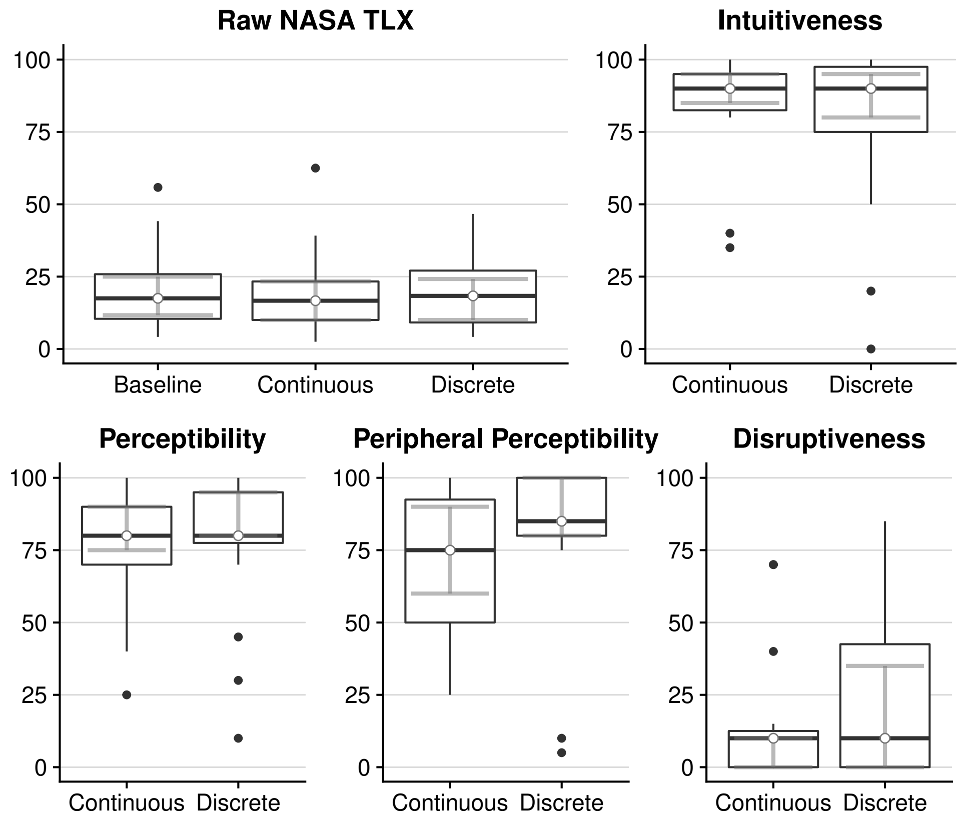


Figure 5.5: Boxplots for the questionnaire results with bootstrapped 95% confidence intervals.

5.1.3.5 Subjective Differences Between the Light Patterns

We asked each participant to rate *intuitiveness*, *perceptibility*, *peripheral perceptibility* and *disruptiveness* for both light patterns. The results are shown in Figure 5.5. The answers are not normally distributed. The median intuitiveness is 90 for *Cnt* (IQR: 12.5) and *Dsc* (IQR: 22.5). The perceptibility rating has a median 80 for both, *Cnt* (IQR: 20) and *Dsc* (IQR: 17.5). The participants gave peripheral perceptibility a median rating of 75 in the *Cnt* condition (IQR: 42.5) and 85 (IQR: 20) in the *Dsc* condition. The disruptiveness received a low median of 10 in both conditions with an IQR of 12.5 for *Cnt* and 42.5 for *Dsc*. Wilcoxon tests did not show any significant differences on a $p < .05$ level for these scales.

5.1.3.6 Interviews

As described above, each participant was given the opportunity to report benefits, drawbacks, characteristics or anything else related to each condition.

Most participants did not report anything for the baseline condition. One person noticed that one would need to look more often and longer into the side-view mirror. Another person felt less confident when deciding for a maneuver. Further, one participant did rather not overtake in uncertain situations.

For both light patterns, five participants emphasized that the light display needs to adapt to the brightness of ambient lighting. Two people think that any display would help independent from its concrete implementation. On the other hand, two people did not like to have a light display, since it was hard for them to focus on the light, the mirror and the street at the same time. They would only use the mirror. One person suggested doing a long term study to investigate the effect after people got used to it.

For most people (11), the *discrete light pattern* informed too late. They already decided for a maneuver, before the light turned on. Three participants sensed a conflict between their estimate and the information given by the display. Also, three people stated that the pattern did not help them at all. Two were not sure what was being displayed, while one person did not understand the timing. Furthermore, two participants waited for the light to turn on and were confused when it did not before they had to decide. In addition, two people did not notice the light pattern at all.

Regarding the *continuous light pattern*, many participants (7) stated that the light should have started to move further in the front. Three people noted they had to focus on the display to decode additional information, like the speed of the rear car. Six participants preferred this light pattern. Five people liked the fact that this light pattern encodes relative speed of the rear left car, while four people liked the encoding of the TTC via the position of the light. Also, three participants stated that this light pattern is easier to perceive because of the movement of the light.

5.1.4 Further Data Exploration

As none of our hypotheses were supported, we were interested in a deeper understanding of the driver behavior. Therefore, we analyzed the impact of both displays on the participant's decision to overtake. Also, we looked at the distance between the street sign and the participant's vehicle at the initiation of the maneuver as a mean of assessing how much a driver waited to decide.

5.1.4.1 Impact on Decision

For the analysis above, we defined requirements that need to be fulfilled to call a maneuver "safe" or "good" and compared the number of them. However, as shown in Table 5.1, our variations of speed and TTC of the rear left vehicle also changed the time and distance gap of it.

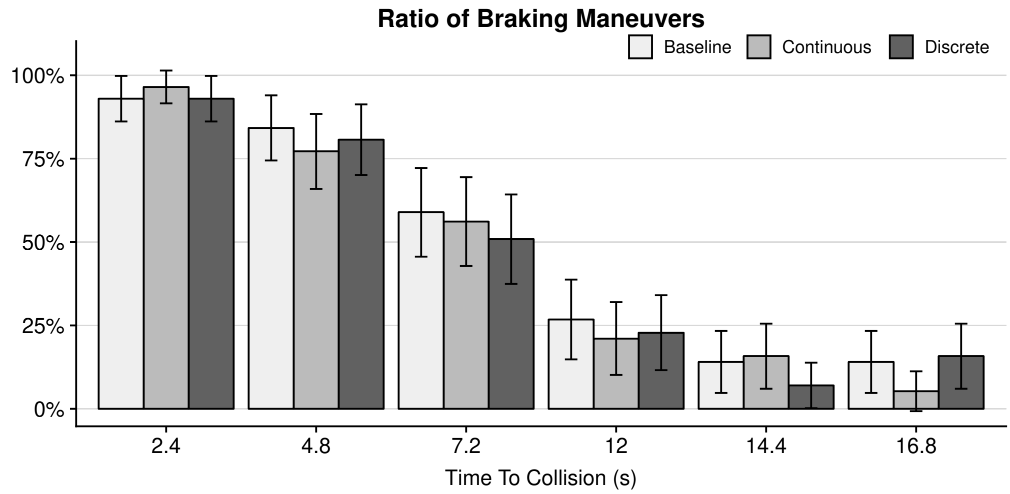


Figure 5.6: Barplots with bootstrapped 95% confidence intervals showing the mean ratio of braking maneuvers per participant, condition, and TTC.

Figure 5.6 gives an overview of the ratio of braking maneuvers per TTC of the approaching rear left vehicle after the participant passed the sign. As no display was active after a TTC of more than 7.5s, it is interesting to observe that participants seem to brake less often with the discrete pattern at a TTC of 14.4, while at a TTC of 16.8 using the continuous patterns seems to lead to the fewest braking decisions. Apart from that, the variations in the results are too big to assume significant effects, in line with the results for the overall number of safe decisions (R_1).

Figure 5.7 gives an overview of the ratio of braking maneuvers per time and distance gap classes of the approaching rear left vehicle after the participant passed the sign. We chose to split the observed distance gaps at 26.67m and 66.66m because the resulting distance classes have the same number of observations. Also, about 65m to 80m can be considered as a safe distance in our use case, depending on the speed of the rear left car. The 2s time gap threshold is commonly used to assess if a gap is safe. Similarly, a gap of 1s is considered to be too close to avoid an accident. The confidence intervals do not indicate significant differences. There may be a trend towards braking less often with the discrete pattern at a very close distance ($< 26.67m$ or $< 1s$). Also, while not significant, using the continuous pattern led to fewer braking maneuvers at a close distance between 26.67m and 66.66m on average.

5.1.4.2 Impact on Time to Decision

The time to decision cannot be measured because we do not have a trigger with a well-defined onset. However, participants were instructed to not react before they passed the traffic sign. Therefore, the distance between the traffic sign and the participant's vehicle

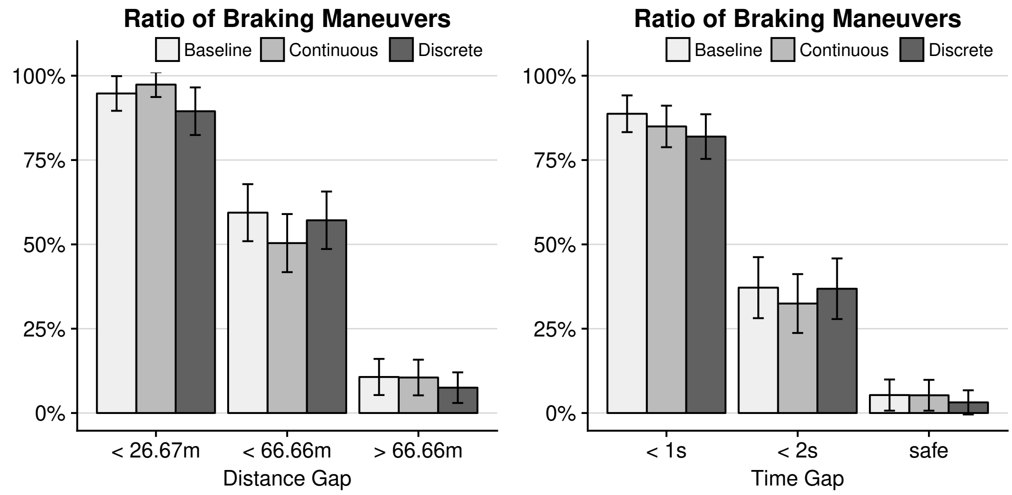


Figure 5.7: Barplots with bootstrapped 95% confidence intervals showing the mean ratio of braking maneuvers per participant, condition, and classes of distance gaps (left) and time gaps (right).

at the decision (initiating braking or steering) may indicate how much a driver hesitated to decide.

The mean distances to the traffic sign at the time a driver initiated a driving maneuver are shown in Figure 5.8. The differences do not seem to be significant. Still, considering that lane change maneuvers at a TTC of less than 5s and braking maneuvers at a TTC of more than 14s are not common and thus their values not meaningful, there seems to be a trend that participants wait longer before they initiate a maneuver.

Similar to the observations per TTC, most differences are not significant with a trend towards participants taking more time to decide with an ambient light display. However, the difference between the discrete light pattern and the baseline pattern for initiating a lane change maneuver at a distance of more than 66.66m is significant. The mean distance in baseline driving for this condition is 63.2m (CI 95%: $[54.4, 72.0]$) and with the discrete pattern 83.7m (CI 95%: $[75.5, 92.0]$). The average difference between both, 20.6m, corresponds to about .62s at the driver's speed of 120km/h. We observe the same trends for the time gap groups. Again, we see a significant difference between baseline driving (M: 63.5m, CI 95%: $[53.1, 74.0]$) and driving with the discrete pattern (M: 84.3m, CI 95%: $[74.4, 94.2]$) in the safe distance class when changing lanes. The difference of 20.8m corresponds to .62s.

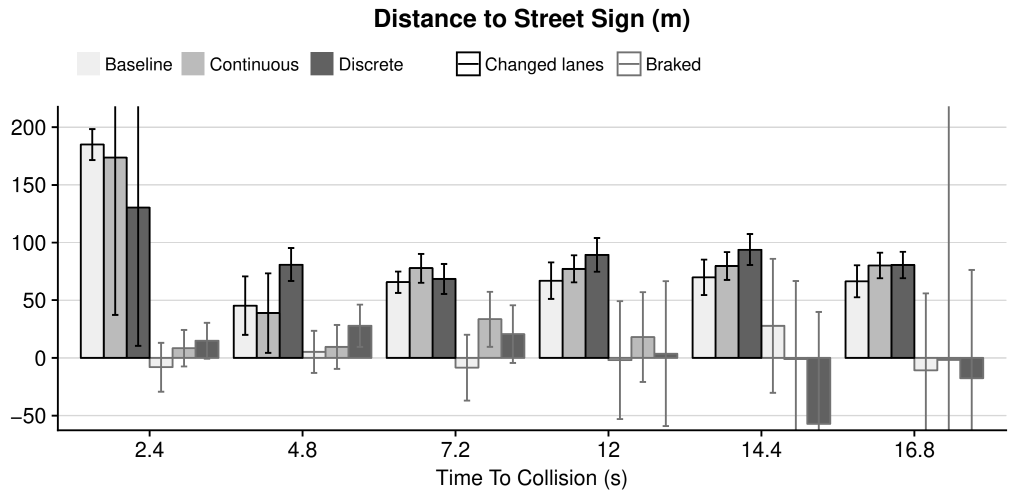


Figure 5.8: Barplots with bootstrapped 95% confidence intervals showing the mean distance towards the passed street sign per participant, condition, and TTC. We further split this plot by the decision of the driver because they are very different. Distances at braking maneuvers have a gray outline, lane change maneuvers a black one. We observed only a few overtaking maneuvers at a TTC of 2.4s. Similarly, only a few drivers braked at a TTC of more than 12s. Thus, due to the few observations, the confidence intervals are very big for these observations.

5.1.5 Discussion

Using the discrete pattern decreased the number of good maneuvers by 21.87%, compared to the baseline, but we did not see a significant difference between the baseline and the continuous light pattern. Further, the RTLX measures showed a rather low workload without significant differences. Therefore, our hypotheses are not supported.

We expected to see a significant effect between the discrete pattern and baseline because it was based on the timings of ISO 17387. The standard focuses on requirements for sensors and warnings. However, the results from our interviews suggest that drivers already decided on a maneuver before a light display was activated. Further, giving the information too late to the driver, as in the discrete pattern, seems to make the assistance not only worthless but also confuses the driver and leads to worse performance. This explanation is supported by the longer times that drivers take to decide for a maneuver with the discrete pattern. The later decisions lead to a closer distance to the vehicle in front, which explains the significantly fewer number of safe overtaking maneuvers with the discrete pattern.

The ratio of braking maneuvers falls below 50% before the time gap is above 2s (see Figure 5.7). However, if drivers were making safe decisions, this should happen later. The corresponding point from a TTC perspective is between 7.2s and 12s. Hence, we

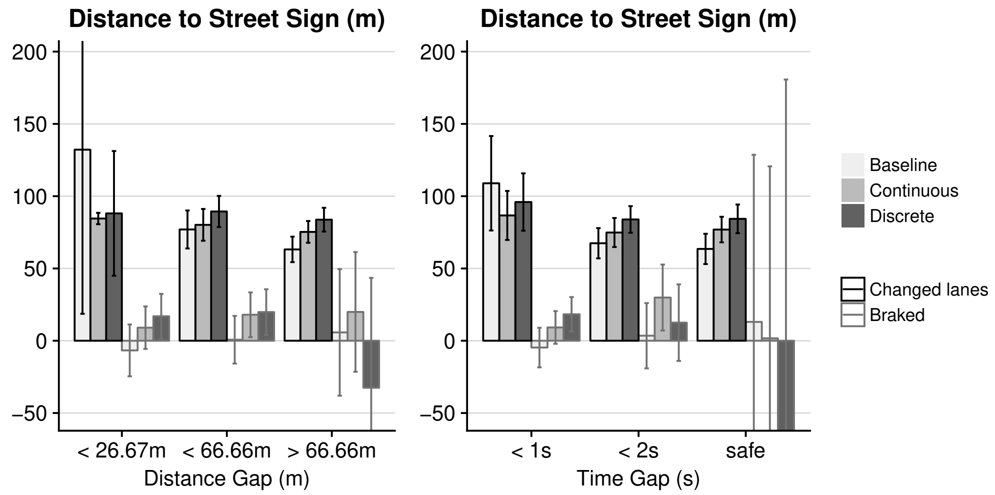


Figure 5.9: Barplots with bootstrapped 95% confidence intervals showing the mean distance towards the passed street sign per participant, condition, and distance gap (left) or time gap (right). We further split this plot by the decision of the driver because they are very different. Distances at braking maneuvers have a gray outline, lane change maneuvers a black one. We observed only a few overtaking maneuvers at a small gap of <26.67m or <1s, respectively. Similarly, only a few drivers braked at a big gap of more than 66.66m or 2s, respectively. Thus, due to the few observations, the confidence intervals are very big for these observations.

argue that drivers need to be more assisted in this class of situation. However, this is limited to our scenario and setup, and more research has to be done to define a model of driver's uncertainty. Based on these results, we argue that drivers need assistance from LCDAS during the decision making, which seems to be before the defined warning time. However, our experiment was rather small and more research has to be done to support our assumptions. Another limitation of our study is that all experiments took place in our driving simulator. Hence, the light patterns should be tested in a real-life driving environment. Also, a long-term study could show if drivers get used to the light display and therefore behave differently.

5.1.6 Summary

We presented two light patterns that were designed to assist drivers in lane change decisions. However, we did not observe any performance improvements (*RQ*2). On the contrary, participants made significantly fewer safe driving maneuvers with the discrete light pattern and felt that the status update came too late to support their decision-making for both light patterns.

The feedback from participants was positive for the continuous pattern. We derive from the interviews that a major reason for the bad performance was that drivers were informed too late because of the chosen thresholds of the distance classes. Therefore, we conclude that the warning levels from ISO 17387 are not well suited to support drivers during decision-making in our scenario.

With regard to the next design iteration, we found that most participants preferred the continuous pattern, for example, because it gives additional information. However, it may benefit from positioning it further to the front. Therefore, this encoding should at least start earlier to give information.

5.2 Adapting the Display to Driver Uncertainty

In this section, we introduce two new designs for assisting the driver during lane changes with ambient light as published in [LHB15]. First, a light pattern that is a simplified redesign of the continuous design described in Section 5.1 with new timings. Second, a pattern that does not only move according to the distance of the rear car but also changes its brightness according to a simple model of a driver's uncertainty to get his or her attention in uncertain situations. We found that using the *adaptive* pattern led to faster decisions and therefore to a smaller probability of violating safety distances. Another pattern that adapts to the driver's uncertainty but also includes a color change to warn about a dangerously close vehicle is discussed in Section 5.4.

As we discuss in [LYHB19, submitted for publication], adapting an assistance system to a driver's mental state can influence his or her performance and satisfaction positively. For example, a spoken dialogue system that adapts to the user's experience utilizing user models has been proposed in [HH06, JL14]. Another example is a real-time workload estimator that displays the current traffic situation [PMGK03]. The system assesses the current mental workload based on the traffic situation and redirects phone calls if the workload is above a given threshold to avoid a further increase. Similarly, a voice information system that adapts to mental workload has been developed in [UiKH$^+$02]. In this system, the workload is mainly derived from how the accelerator pedal is released.

The examples above show that it can be beneficial to adapt interfaces to drivers' mental states. As one aspect of this state, we consider driver uncertainty in our work. It can prolong the decision-making process and cause longer reaction times [PK14], which further leads to lane change crashes. In addition to traffic safety, uncertainty is also assumed to influence trust and the use of systems [Kol94, LS04]. Also, providing frequent warnings while drivers are certain, is perceived as annoying and will lead to the disuse of systems [BPPK15, Bre13]. Driver uncertainty can be defined as a "*driver's difficulty in a given lane change situation to decide whether to overtake or to wait*" [YEBL16]. We will use a simple model of driver uncertainty and adapt one of our light patterns to it.

5.2.1 Design of the New Light Patterns

The light patterns presented in Section 5.1 did not affect driver performance positively. The participants mentioned that the display did not give them the needed information before they decided which maneuver to make. As participants preferred the continuous pattern, we decided to build the new designs on top if this pattern.

Both new patterns are now activated at a TTC of 20s at the B-pillar, as depicted in the top row in Figure 5.11, which is 2.61s time gap in the scenario for the later evaluation. This activation time ensures that the information is not displayed too late for the driver. The moving light cue reaches the A-pillar at a TTC of 2s (or .26s time gap in our scenario) and stays there until the other car passed. Thus, the function for the position is as follows:

$$pos(ttc) = \frac{ttc - 2s}{20s - 2s}, \text{ if } 2s < ttc < 20s$$

The position of the light cue is mapped to the array of LEDs. The light cue has a radius of two LEDs. The brightness has a peak at the center and hits zero at the end of the radius. For smooth transitions, the light is interpolated. The function for this interpolation is as follows for the 57 LEDs:

$$brght_{LED_i} = 1 - \frac{|i - 57 \cdot pos|}{2}$$

The color and brightness of both designs were defined after a small pilot study with three experts: one for the simulator, one for driver distraction, and one for driver's certainty. The setting was the same as the one described later. The only differences were variable colors and brightness levels of the light as well as the initial speeds of the left car.

A snapshot of the final design is shown in Figure 5.10. We used a neutral color to remove a possible call to overtake (e.g., green) or brake (e.g., red) for the light patterns. We discussed that white, blue and purple might be used as a neutral color in Chapter 4. While *white* is also proposed to be used in "Preliminary Human Factors Guidelines for Automated Highway System Designers" [LBD+98], we withdrew it because it interfered with the simulated white markings of the street borders and confused our pilot participants. Further, *blue* was perceived as too close to the simulated color of the sky and appeared to be distracting. *Purple* (RGB: 100,0,100) was considered to be neutral too and was therefore used for our patterns.

The difference between both light patterns is the brightness of the light, which is constant or adapts to the assumed uncertainty of the driver. Both patterns were designed to not distract drivers while continuously informing them about approaching rear cars on the adjacent lanes in order to avoid surprises.

Figure 5.10: Our driving simulator during the experiment. The purple light gives information about the distance to an approaching rear car on the target lane via its location and brightness. In front is a slower car on the same lane and a faster car on the left lane. The driver now has to decide if he or she wants to overtake.

Figure 5.11: Example states of both light patterns. Left: Adapting light pattern; Right: Constant light pattern. First row: $TTC = 19s$, $distance_{rear} = 95m$; second row: $TTC = 10.8s$, $distance_{rear} = 54m$; third row: $TTC = 9s$, $distance_{rear} = 45m$. In contrast to the constant pattern, the brightness of the adapting pattern is highest around $54m$ and decreases to both ends.

5.2.1.1 The Constant Light Pattern

The position of the light changes as described above. The brightness of the light is constant at 39% of its maximum. Thus, the brightness of each LED is "$.39 \cdot brght_{LED_i}$". This value was chosen to fit the ambient light conditions in our simulator. It should be bright enough to be seen by the drivers without distracting them. In a real-life setting, this value would adapt to the ambient light conditions of the vehicle. This light pattern can be seen for different distances of the rear left vehicle in Figure 5.11 on the right side.

5.2.1.2 The Adapting Light Pattern

The idea for this pattern is to catch the drivers' attention if they are uncertain about which action to take. At the same time, the light should not distract when the driver decided for a maneuver following the suggestions in our design workshop (see Section 4.5.3.1).

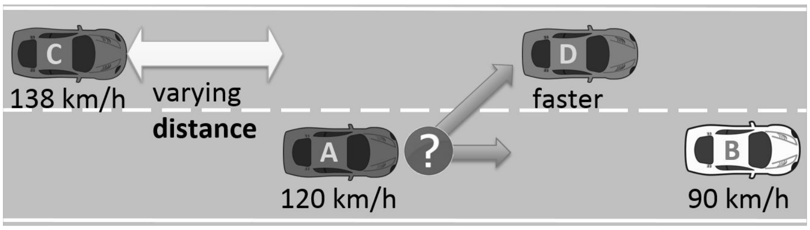


Figure 5.12: Overview of the scenario used for our driving simulator experiment: (A) the ego-vehicle; (B) the slower car in front, driving at a speed of 90 km/h; (C) the faster rear left car, driving at 138 km/h; (D) the faster car starting to the left of the participant's car with varying speed. The initial distance to the front car B is manipulated to be at a gap of 2s when car C reached a TTC of 7.5s, 10s, $12.5s$, $15s$ *or* $17.5s$*, if the participant sticks to 120 km/h. The initial distance to the left car D is* $0m$ *while the speed was varied in a way to achieve a distance of* $1s$ *when car C reaches the target TTC.*

The model for driver uncertainty that is later used in Section 5.4 was not ready when we developed this light pattern. Thus, we defined a simplified model, based on our observations in Section 5.1. We fixed the speed of the rear left car to $138km/h$ and derive a peak at a rear-to-front distance of $54m$ from our previous observations. The model then assumes that the uncertainty of a driver has a Gaussian distribution with a maximum at the peak of $54m$ for a fixed Δ_{speed} of $5m/s$. This simple uncertainty model neither contradicts our observations in the previous study nor the first results of Yan et al. in [YWL14]. To increase the salience at uncertain distances, we connected this model to the brightness of the light cue by defining the following brightness function:

$$brightness = (.39 - .03) \cdot e^{-\frac{1}{200}(dist-54)^2} + .03$$

We chose the maximum (39%) and minimum brightness (3%) to not blind the driver and to be just bright enough to be visible. The term $\frac{1}{200}$ controls the ascent of the brightness and was found exploratory in the pilot study. The individual LED's brightness is still interpolated using the previously defined function and can be expressed as "$brightness \cdot brght_{LED_i}$". Examples of different states for these light patterns are shown on the left side in Figure 5.11.

5.2.2 Driving Simulator Experiment

After we developed the above defined light patterns and integrated them into the driving simulator (see Section 3.3.3), we evaluated the effect of these patterns on driving performance (R_2). The basic scenario is similar to the one used in the experiment presented in Section 5.1. On a simulated highway, a driver has to decide if he or she wants to change lanes to pass a slower vehicle in front or to brake and let a faster car pass. In contrast to the previous experiment, we removed the traffic sign and added a third vehicle to the left of the driver as sketched in Figure 5.12. Further, the driver's car was equipped with a cruise control system that accelerates the car to 120km/h.

We define the following hypotheses and explain our reasoning below.

H_1: With any ALD, drivers are less likely to violate the safety distance to the rear vehicle after changing the lane

The ALDs present the distance to the rear car. Thus, they should help the driver to violate the distance to the rear car less often. The time gap is measured as $tgap_{rear} = distance_{rear}/speed_{rear}$, where *distance* is the rear-to-front distance gap to the car in front. A violation is defined as $tgap_{rear} < 2s$ when the driver reaches the left lane. For this hypothesis, we only analyzed trials where a driver decided to overtake for all three conditions.

H_2: With any ALD, drivers are less likely to violate any safety distance

If the ALDs help drivers to asses the distance to the rear car, we expect it to also affect the distance to the other cars. We argue that an easier assessment of the distance to the rear car will free resources to better concentrate on the other cars. Hence, in each trial, we measured if a safe time gap of two seconds was violated to any other car at any time during the trial. The time gap to the car in front is given as $tgap_{front}$, and the gap to the left car is defined as $tgap_{left}$. $tgap_{left}$ and $tgap_{rear}$ are not considered, whenever a car is on the right lane. Also, $tgap_{front}$ is not considered anymore, after a driver changed to the left lane. The pilot study showed that participants never waited for the safety gap of $2s$ to the left car before overtaking. Hence, we also analyzed the data without $tgap_{left}$.

H_3: With any ALD, drivers will decide faster on which maneuver to make

We are interested in the overall time a driver needs to begin a maneuver. We argue that drivers will decide faster when our ALDs assists them.

H_4: The adapting pattern is perceived as less obtrusive

One of our goals is to create an ambient display that does not distract the driver. We expect the adapting light pattern to be less obtrusive than the static pattern because it is less salient when we expect the driver to be certain about the situation.

5.2.2.1 Experiment Design

We designed the evaluation as a within-subjects, repeated measures experiment with three conditions. In the *baseline* condition, the light displays are inactive. In another condition, the earlier described *constant* light pattern is used to display the distance to a rear left car. In a third condition, the distance is encoded using the *adaptive* light pattern.

The order of conditions is counterbalanced, and the order of driving tasks within each condition is randomized.

5.2.2.2 Procedure

We started the experiment with an introduction by the experimenter and informed participants about their rights and privacy regulations. Then we asked them to sign a written informed consent form. Afterwards, we informed the drivers about the procedure and explained how to use the driving simulator. Before starting the driving trials, we handed out the first part of the questionnaire regarding demographic data.

The order of conditions was counterbalanced. Each condition started with 15 training trials, without data being recorded. After a short break, participants continued to drive for 40 trials. Everyone drove the same trials in each condition but in a randomized order.

As depicted in Figure 5.12, the speeds of an approaching rear left car and the one in front were fixed to $138km/h$ and $90km/h$ in every trial. The driver's car was equipped with cruise control that accelerated the car to $120km/h$. Further, the participants were instructed to only accelerate if they wanted to overtake, and only to brake if they decided not to overtake. We designed the trials in a way that participants had to decide at a TTC_{rear} of either $7.5s$, $10s$, $12.5s$, $15s$ or $17.5s$ if they stuck to $120km/h$. We varied the time until this decision from $4.5s$ up to $16s$ meaning the gap to the car in front would be $2s$ (or $66.7m$) and the gap to the faster car to the left $1s$ ($33.3m$). The detailed initial distances and speeds can be seen in Table 5.3. Initially, we planned to have a gap of $2s$ to the left car as this is considered to be a safe distance. However, we observed in our pilot study that drivers would most likely start overtaking about a second earlier than that. Since drivers can change their speed, the measured distances will most likely not meet our expectations. However, we think that the differences in the distance to the front and rear car will have an impact on the decision of the driver and will help us not to have a too specific set of trials.

After each condition, the participants were asked to rate if they felt confident with their decisions, if they felt disrupted by the light, if it was hard to make decisions and if they were satisfied with their performance on a five-point Likert scale with 1 meaning full rejection of a statement and 5 being "full agreement". We also invited participants to give feedback on the experiment or the light display. Each experiment ended with a wrap-up discussion and took about 60min.

5.2.2.3 Participants

30 drivers (14 female), with an average age of 24.6 years (SD: 5.2) took part in our study. The average driven kilometers per year ranged from 20km to 12,000km with a mean of 2,471 (SD: 2,824). Participants obtained driving licenses for an average of 7.1 years (SD: 4.7). They received 10 € for taking part in the study.

Initial values			Expected values at time of decision				
$speed_{left}$	$distance_{front}$	$distance_{rear}$	**TTD***	$distance_{rear}$	$tgap_{rear}$	TTC_{rear}	**Training?**
35.67	200.00	117.50	16.00	37.50	0.98	7.50	
35.79	193.06	113.33	15.17	37.50	0.98	7.50	yes
35.94	186.11	109.17	14.33	37.50	0.98	7.50	yes
36.10	179.17	105.00	13.50	37.50	0.98	7.50	yes
36.05	181.25	118.75	13.75	50.00	1.30	10.00	
36.22	174.31	114.58	12.92	50.00	1.30	10.00	yes
36.42	167.36	110.42	12.08	50.00	1.30	10.00	yes
36.65	160.42	106.25	11.25	50.00	1.30	10.00	yes
36.58	162.50	120.00	11.50	62.50	1.63	12.50	
36.83	155.56	115.83	10.67	62.50	1.63	12.50	yes
37.13	148.61	111.67	9.83	62.50	1.63	12.50	yes
37.48	141.67	107.50	9.00	62.50	1.63	12.50	yes
37.37	143.75	121.25	9.25	75.00	1.96	15.00	
37.77	136.81	117.08	8.42	75.00	1.96	15.00	yes
38.26	129.86	112.92	7.58	75.00	1.96	15.00	yes
38.86	122.92	108.75	6.75	75.00	1.96	15.00	yes
38.67	125.00	122.50	7.00	87.50	2.28	17.50	
39.39	118.06	118.33	6.17	87.50	2.28	17.50	yes
40.33	111.11	114.17	5.33	87.50	2.28	17.50	yes
41.63	104.17	110.00	4.50	87.50	2.28	17.50	yes

* TTD: time to decision. The minimum time until $tgap_{front} \leq 2s$ with $speed_{ego} = 120km/h$.

Table 5.3: The initial distances and speeds for every trial, as well as the predicted distances at the time of decision. Other values are fixed: $speed_{front} = 25m/s$, $speed_{rear} = 38.33m/s$ and initially $dist_{left} = 0$. The drivers were instructed to stay at $120km/h$ (or $33.33m/s$). All trials were run twice, and the order was randomized in each condition. A subset of the trials was also used once in the training as highlighted. The time to decision (TTD) is defined as the minimum time until $tgap_{front} \leq 2s$ at a constant ego speed of $120km/h$. The expected values are only for orientation and were not taken into account for any analysis.

5.2.2.4 Results

We collected a total of 3,600 observations (1,200 per condition). However, for technical reasons, we had to remove trials where drivers stayed on the left lane until the next trial started. We also removed all corresponding trials in the other conditions to have complete cases. Thus, 3,537 observations (1,179 per condition) remained for analysis. In the following, we present the impact of the light patterns on the distances to other cars, violations of safety distances, time until the start of maneuvers, and qualitative feedback.

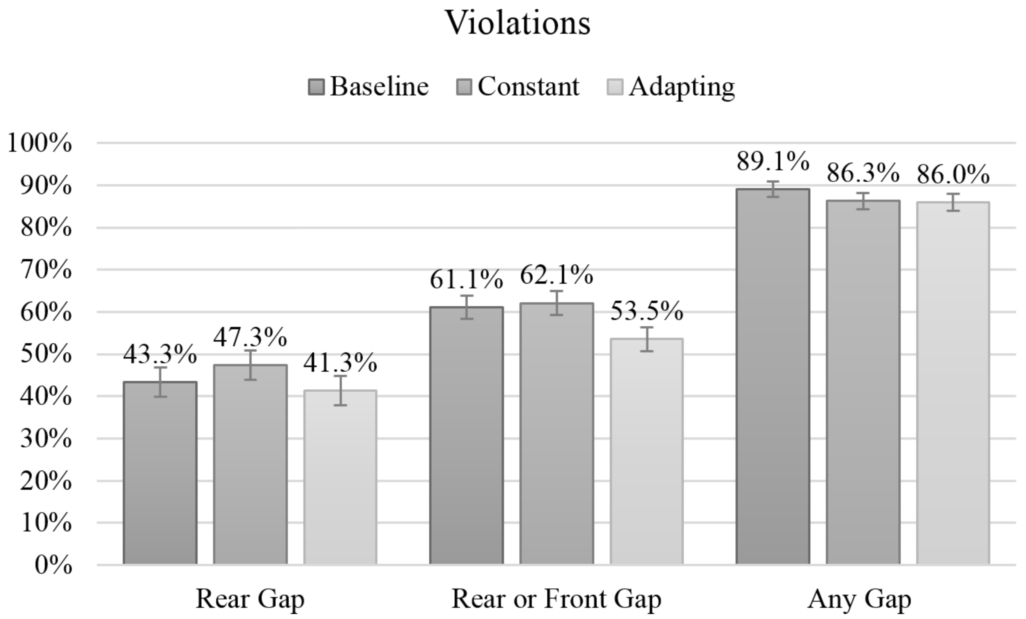


Figure 5.13: Mean values for percentage of violated safety gaps with their 95% confidence intervals separated by the condition. Using the constant light pattern we saw a higher percentage of violations of the gap to the rear car. The number of violation to rear or front car was lowest using the adapting pattern. Without assistance, participants violated the safety gap to any other car more often.

Violations of Safety Distances

Regarding H_1, we are interested in the distribution of violations of safety distances to the rear car while overtaking. We only analyzed cases where drivers changed lane in all three conditions, which was the case in about two third of the trials (2,403 observations). Figure 5.13 shows the mean percentage of violations per participant and condition.

With the *constant* pattern, the participants were most likely to violate a distance to the rear left car (M: .47, SD: .50). They performed better without assistance (M: .43, SD: .50). When using the *adaptive* pattern, they violated safety gaps less often (M: .41, SD: .50). Since the data is binomially distributed, we used a Cochran's Q test to check for significant differences. We found a difference in violations among the three conditions ($\chi^2(2) = 14.53$, $p < .01$). A pairwise comparison using continuity-corrected McNemar's tests with Bonferroni correction revealed that significantly more participants violated the safety distance to the car behind with *constant* pattern compared to the *baseline*, while Cramer's V does not reveal a relevant effect size ($p < .05, V = .06$). Compared to the *adaptive* pattern, the difference is significant but small ($p < .01, V = .10$).

Regarding H_2, we are interested in the distribution of violations of safety gaps to any other car. We did not filter the observations as for H_1. Hence all 3,537 were analyzed. In the *baseline* condition, the participants were most likely to violate a distance to any

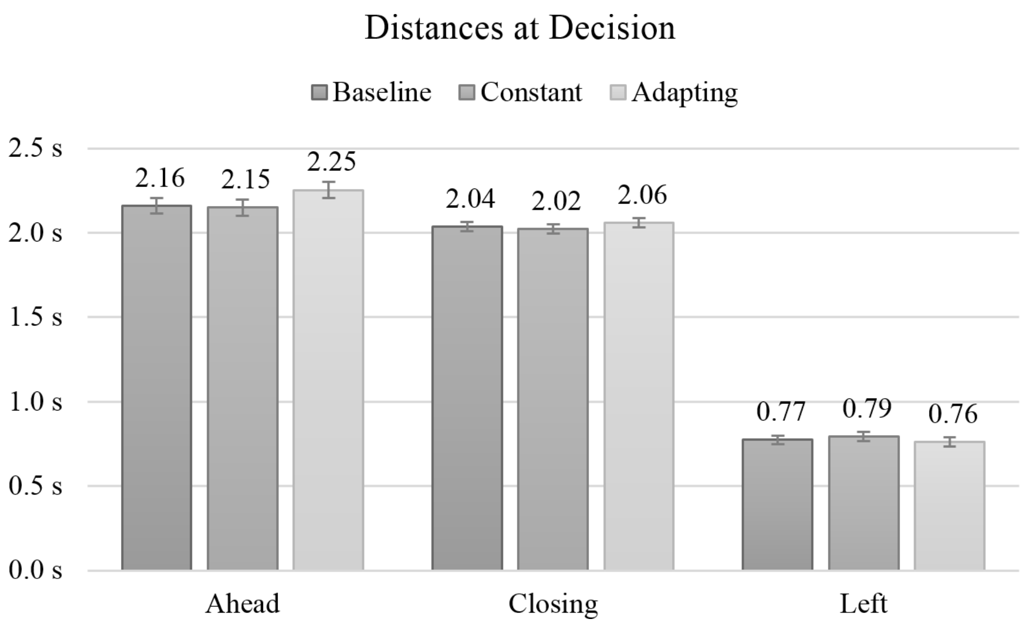


Figure 5.14: Mean values for time gaps to other cars with their 95% confidence intervals separated by the condition. The gap to the front vehicle was highest when using the adapting pattern. There were no significant effects on the other gaps.

car (M: .89, SD: .31). With *Constant* (M: .86, SD: .34) and *Adapting* (M: .86, SD: .35) they were less often violating safety gaps. With a Cochran's Q test, we found that there is a significant difference in violations among the three conditions ($\chi^2(2) = 7.47$, $p < .01$). A pairwise comparison using continuity-corrected McNemar's tests with Bonferroni correction revealed that significantly more participants violated a safety distance to any car without light compared to the *constant* ($p < .05, V = .06$) and *adapting* pattern ($p < .05, V = .06$). However, both effect sizes are very small.

Since the left car was set very close on purpose, we also analyzed violations to the distance to the front and the rear car only, again with all 3,537 observations. With *Constant* active, the participants were most likely to violate a safety distance to any of the two cars (M: .62, SD: .49). Without assistance, participants performed on the same level (M: .61, SD: .49). With *Adapting*, participants violated safety gaps less often (M: .54, SD: .50). With a Cochran's Q test, we found that there is a significant difference in violations among the three conditions ($\chi^2(2) = 31.35$, $p < .01$). A pairwise comparison using continuity-corrected McNemar's tests with Bonferroni correction revealed that significantly less participants violated a safety distance to the cars with *Adapting* compared to *Baseline* ($p < .01, V = .10$) and *Constant* ($p < .01, V = .12$).

Distances to Other Cars

We already showed that the safety distance to other cars was violated less often with the *adapting* pattern. The following gives details about the time gaps to the other cars, as shown in Figure 5.14. To use ANOVAs, all measurements were tested for homogeneity of variance using Levene's test. Further, sphericity was tested using Mauchly's test.

A participant left the most space to the car in front in the *adapting* condition (M: 2.25s, SD: .83). The gap is smaller in the *baseline* condition (M: 2.16s, SD: .81). Also within the *constant* condition, the gap is smaller (M: 2.15s, SD: .84). A one-way repeated-measures ANOVA revealed a significant effect ($F(2) = 5.59$, $p < .01$) between the conditions. A pairwise comparison using paired t-tests with Bonferroni adjustments showed significantly bigger gaps, while Pearson's r shows large effect sizes with *Adapting* compared to *Baseline*, ($p < .01$, $r = .71$) and *Constant* ($p < .01$, $r = .74$).

When analyzing the gap to the rear left car, we only considered trials where a participant started an overtaking maneuver in all three conditions. Hence, we analyzed 2,403 measurements. The mean gaps for all three conditions are similar with 2.04s for *Baseline* (SD: .40), 2.02s for *Constant* (SD: .40) and 2.06s for *Adapting* (SD: .41). The differences are not significant ($F(2) = 1.56$, $p = .21$).

Before the study, we assumed that people would initiate an overtaking maneuver at a gap of about $1s$ to the car on the left lane, ignoring safety gaps. Our measurements show that they overtook earlier at about $.8s$ on average. With the *adapting* pattern the gap was smallest (M: .76s, SD: .40), followed by *Baseline* (M: .77, SD: .37) and *Constant* (M: .79s, SD: .39). An ANOVA test did not show significance ($F(2) = 1.58$, $p = .21$).

Time to the Start of the Maneuver

Concerning H_3, we are interested in the time a driver needs to initiate a maneuver. While the initial distances to the other cars have an impact on this measurement because a driver has to wait until the gap to the left car is big enough, we expected that using the light display resulted in faster decision-making and thus in a shorter time to the start of a maneuver. We defined the start of a maneuver as the moment when a driver hits the brake or enters the left lane with at least the left tires. We expect these data to be normally distributed. Again, all measurements were tested for homogeneity of variance using Levene's test and for sphericity using Mauchly's test before running ANOVAs. The average time per condition until a maneuver is initiated is shown in Figure 5.15.

With *Constant*, the participants needed the most time to start a maneuver (M: 8.94s, SD: 3.44). Without assistance, participants needed three hundredths less time (M: 8.91s, SD: 3.49). With *Adapting*, they started faster (M: 8.58s, SD: 3.48). With one-way repeated-measure ANOVA, we found a significant effect of the used light pattern on the time to maneuver ($F(2) = 3.79$, $p < .05$). A pairwise comparison using t-tests with Bonferroni adjustments revealed that participants were faster with *Adapting* compared to *Baseline* ($p < .01$, $r = .78$) and *Constant* ($p < .01$, $r = .79$). The effect sizes are large.

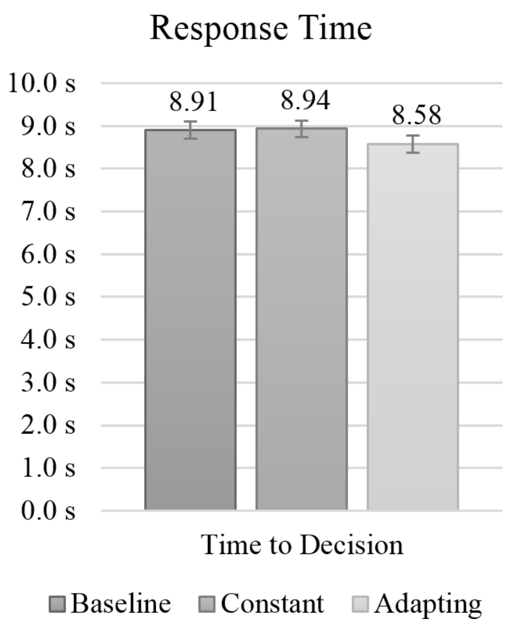


Figure 5.15: Mean values for the time until a driver decided per trial with their 95% confidence intervals separated by the condition. The time to decision was lowest when using the adapting light pattern.

Results of Questionnaire

The scales of our questionnaire are shown in Figure 5.16. As the results of our questionnaire are not distributed normally, we ran Friedman tests to find differences between the light patterns but did not observe significant effects. The participants did not feel distracted by the display (Mdn: 2, $\chi^2(1) = .09, p = .76$). Also, they found it rather easy to make a decision (Mdn: 2, $\chi^2(2) = .45, p = .80$). In addition, participants felt mostly to have taken the right decisions (Mdn: 4, $\chi^2(2) = 2.23, p = .33$) and were rather satisfied with their performance in all three conditions (Mdn: 4, $\chi^2(2) = 1.27, p = .53$).

Qualitative Feedback

After the questionnaire, we asked the participants to give additional feedback. Eighteen people stated that using an ALD helped them, while 7 stated it did not. Eleven people said they defined a fixed point and only braked if the position of the light source was in front of it. Eight people stated the light did not influence them. Four participants said they did not understand the encoding. One person thought the light was a call to overtake. Four participants mentioned that the light could be distracting. Seven people did not see a difference between *Adapt* and *Constant*. Two participants said that the light pattern was starting too early.

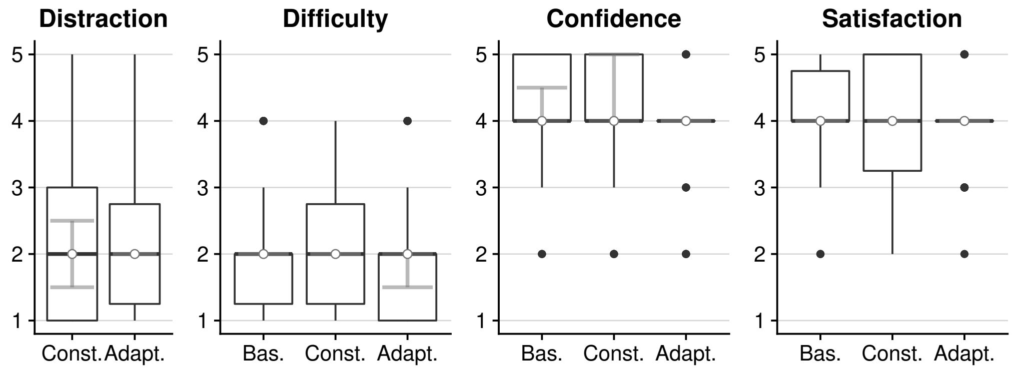


Figure 5.16: Boxplots and bootstrapped 95% confidence intervals for the medians of questionnaire results, separated by the condition. Participants were asked to reject or agree to four statements per condition. Their answer could range from 1 *(full rejection) to* 5 *(full agreement). The statements were "I felt* distracted *by the display", "I found it* difficult *to decide which maneuver to make", "I felt* confident *that I made the right decisions", and "I am* satisfied *with my performance".*

5.2.3 Discussion

The first hypothesis (H_1) is about the gap to the rear left car, displayed by the patterns. Using an ALD resulted in a 4% to 6% lower probability of drivers violating the safety gap. This result supports our hypothesis.

The second hypothesis (H_2) regarding fewer violations of safety distances was supported for both light patterns. Also, since drivers will in most cases overtake before the left car is two seconds away, the second measurement regarding safety distances to the rear and the front car only shows that the use of the adapting light pattern leads to about 7% fewer violations of those safety gaps. Looking further into it, we saw a significant difference in the gaps to the front. On average, the gap was about $.1s$ bigger with the *adapting* pattern, which is $3.33m$ at $120km/h$. This is already an indicator for H_3 since a driver has to start a maneuver earlier to keep a safe gap to the front.

We measured how long it took the drivers to start a maneuver to validate the third hypothesis (H_3). We saw that using the *adapting* pattern led to faster decisions (about $.3s$ on average) compared to the other light pattern and the baseline condition. This supports our hypothesis.

For H_4, we wanted to see if the *adapting* light pattern is less obtrusive than the other pattern. The questionnaire results do not support this hypothesis. However, participants felt rather not distracted by both light patterns.

Overall, the participant's feedback was positive for both displays. However, many participants stated that the display either did not help them or that they did not understand the encoding. Also, the questionnaire and general feedback of the participants indicate that the constant and adaptive pattern were not perceived as very different. This result is interesting, considering the observed effect on the drivers' decisions.

5.2.4 Summary

In Section 5.1, we argued that using a light pattern that starts to be active at a TTC of $7.2s$ as proposed in ISO 17387 [ISO08] does not work because that is too late to help drivers during their decision-making. In this study, we were able to discover a significant driving performance increase with the new adaptive pattern that starts at a TTC of $20s$ and adapts its brightness to a model of driver uncertainty (R_2). Our findings also indicate that using a model of a driver's state is essential to only support him or her if assistance is needed. However, more research has to be done to refine the light pattern as well as to define a model of driver's certainty in order to see significant effects in various overtaking scenarios with varying relative speeds.

5.3 An ALD for an LCDAS in Free Driving

In this experiment, we aim to explore the drivers' gaze behaviors induced by ambient light displays to investigate RQ3. We use a free driving scenario to overcome the limitation of the strictly controlled driving simulator studies. While the other studies in this chapter focus on leftward lane changes, our free driving scenario also includes rightward lane changes. Apart from analyzing the gaze behavior, we also look into how the driving performance is affected by the ALD in free driving (RQ2).

In the following, we first present how we developed new designs for an ambient light pattern that is using time gaps instead of TTC as input. We then present our results regarding the number of unsafe maneuvers, gaze behavior and user experience, which are also discussed in [LYHB19, submitted for publication].

5.3.1 Designing the Ambient Light Pattern

We derived two designs from our previous results, as well as the results of an online questionnaire. For example, our results so far suggest that ALD based LCDAS need to transition smoothly between states not to distract drivers. Furthermore, they must not be visible from the outside to not distract other traffic participants. Specifically to LCDAS, it might be beneficial to encode the time gap instead of the TTC. Complementing our previous results, we realized an online questionnaire, in which we specifically asked for designs that can encode rightwards and leftwards lane change information. We summarize the main results of this questionnaire below.

5.3.1.1 Questionnaire Results

56 people (25 female) with valid driver licenses (self-reported) participated in this survey. In summary, most participants (96%) want to be able to deactivate the display, while 64% agree that it should always be active whenever a vehicle is within sensor range. We asked if participants would like to have blindspot information encoded utilizing another modality besides ambient light. 61% were against sounds, and 59% did not agree to vibro-tactile cues. Thus, we focused on a unimodal design. Regarding possible light cues for leftward information, participants voted against blinking patterns (77%). The most popular encoding is using changing colors (66%), followed by encoding the distance by increasing the cue, e.g., by increasing the number of active LEDs (55%). Most results are similar for rightward information. 63% were against blinking patterns, 63% preferred changing colors as encoding. However, in contrast to the encoding of leftward information, 57% were against encoding the distance to another car utilizing the size of the light cue. Only people who voted for encoding information with color were asked for preferences considering potential colors. The majority preferred starting the color gradient with green (66% leftwards, 67% rightwards) and ending it with red (72% leftwards, 67% leftwards). The most popular alternative starting color is white (25% leftwards, 23% rightwards). The most popular alternative ending color is orange (19% leftwards, 17% rightwards). Four concerns were mentioned more than once: the display should (a) not distract; (b) not blind the driver, passengers or traffic participants; (c) adapt its brightness to ambient lighting conditions; (d) not mislead drivers to not look into the mirrors and over the shoulder.

5.3.1.2 Derived Light Patterns

We derived two designs. For both, we used the display presented in Section 3.3.3. We used the parts of the display below the left and right windows between the A- and B-pillars, as shown in Figure 5.17. However, the patterns differ in size. The first “fixed-size” pattern uses the first 17 LEDs, close to the A-pillar, similar to the final design (see Figure 5.17). The second “increasing” pattern changes its size depending on the gap size.

The thresholds to classify a time gap as safe or unsafe were the same for both patterns. We defined 2.61s as the limit for a safe gap for leftward lane changes, to be consistent with the activation time in our previous experiment: in Section 5.2, we designed the ALD to activate at a TTC of 20s. In the scope of the earlier experiment, the 2.61s gap size is equivalent to 100m because the relative speed between the two cars was fixed to 5m/s (138km/h and 120km/h). For the rightward gap size, the 2.61s-threshold felt too defensive in an informal pilot study, especially as the own car is usually faster than the rear vehicle on the right lane. Therefore, we defined $1.8\,s$ as limit for an unsafe gap for rightwards lane changes. It is based on the German rule of thumb “half of the speed indicator” for anticipatory driving.

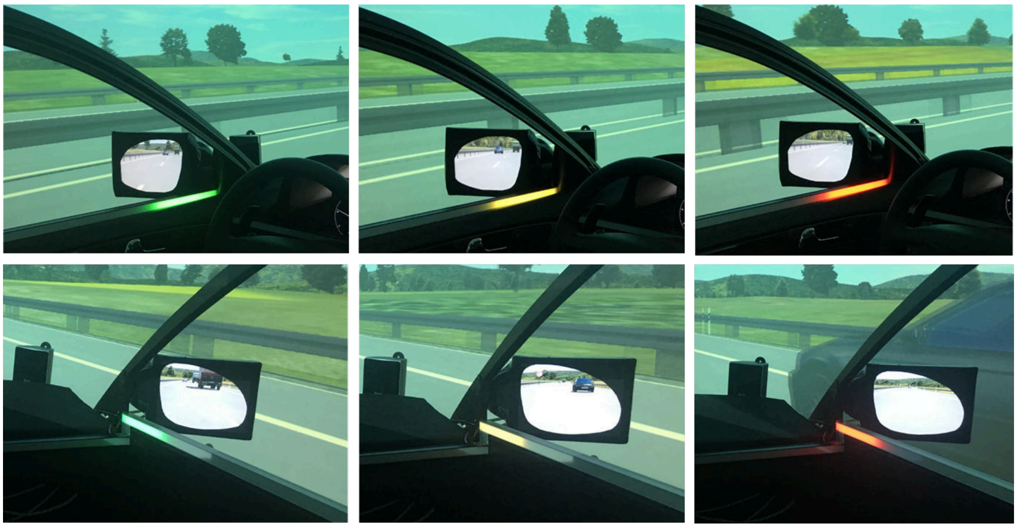


Figure 5.17: The ambient light pattern for the first experiment. Top: cues for leftward maneuvers. Bottom: cues for rightward maneuvers. A large distance is displayed in green (left), a close one in yellow (center) and a dangerous one in red (right).

Both light cues are activated in green when a rear vehicle on the corresponding adjacent lane is closer than the gap threshold and deactivated if the rear vehicle is further away. The gap size is mapped to an RGB-color within a range from 0 to 1 as follows: the red channel is set to $1 - green$, the blue channel to 0, and the green channel to

$$green_{left} = \frac{gap_{left}}{2.61}, green_{right} = \frac{gap_{right}}{1.8}$$

Heuristic Evaluation and Final Design for Experiment

We used a heuristic evaluation to identify issues of our designs. We invited seven experts (four female) with backgrounds in HCI or developing automotive user interfaces to take part. The heuristics were taken from Mankoff et al.'s work "Heuristic Evaluation of Ambient Displays" [MDH+03]. Every expert drove in a simulated two-lane highway scenario. They started without assistance to get used to the simulator until they felt comfortable. Two ten-minute drives followed, each with one light cue. Their order was counterbalanced. We presented the heuristics before each drive and asked the experts to think aloud. After each light pattern, we went through the heuristics and collected the issues. We concluded the experiment with a semi-structured interview to get further feedback on the light patterns.

Most experts perceived both displays as useful and the color change as comfortable. A typical remark was that it should be possible to turn the display off. The light was perceived as too bright on the driver's side and should use fewer LEDs. Also, the distance to the front car on the left target lane should be considered. According to the experts, the fixed-size light pattern provided better situation awareness and was less cognitively demanding than the variable-size pattern. However, the variable-size pattern would be preferable if it used a different way to map the gap size to the display size, e.g., by starting from the B-pillar and filling-up towards the A-pillar. Also, the experts prefer to either use the display's color or size to show the gap size but not both.

5.3.2 Evaluation in Simulated Free Driving Experiment

To evaluate the effect of ALD on driving performance and gaze behavior, we first finalized the design and then measured gap sizes and gaze behavior during lane changes in a driving simulator experiment.

5.3.2.1 Final Design

The light pattern for this experiment is a modified version of the fixed-size pattern. Two of the previous experts tested the new design and did not find new issues. We applied the following adaptations: the number of active LEDs was reduced to 10, or about 7cm, and the brightness to 50% of the maximum possible brightness. Furthermore, the pattern was changed to also take the gap to the front right vehicle into account:

$$green_{right} = min\left(\frac{gap_{rear-right}}{1.8}, \frac{gap_{front-right}}{1.8}\right)$$

5.3.2.2 Hypotheses

The overall goal of this experiment is to understand the effect of ALD on driving (RQ2) and glance behavior (RQ3). Based on our previous experiments and related work, we expect that using ambient light will assist drivers in assessing the situation without requiring their focused attention. Thus, we form the following hypotheses on how using the light pattern will affect the driver's behavior:

H1 The gaps will be closer to a safe margin of 1.8s resulting in fewer unsafe maneuvers.

H2 The glance duration and location probability will be higher towards the forward AOI and lower towards the other AOIs because the ALD provides necessary information in the periphery.

H3 The glance frequencies will be lower because drivers switch their focus less often.

5.3.2.3 Scenario

We designed the driving scenario to simulate free driving on a German two-lane highway with varying speed limits between 100km/h and 130km/h. The traffic adapts to the driver's behavior and creates overtaking opportunities as well as situations where other cars are blocking the fast lane. We did not restrict the participants' control over the car

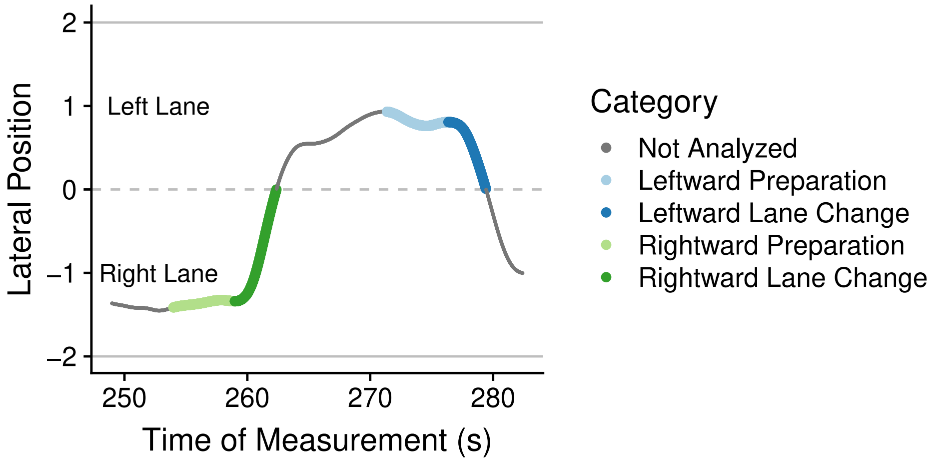


Figure 5.18: An excerpt of the lateral positions for two lane-change maneuvers of one participant. A maneuver lasts from the last low point (leftward) or high point (rightward) until the car enters the target lane. A leftward lane change is marked in dark green and a rightward lane change in dark blue. The light blue and light green areas mark the additional 5s that is considered for the gaze behavior analysis.

but instructed them to drive like they would in their car, which includes obeying the traffic laws.

5.3.2.4 Measurements

We chose a within-subject design to account for individual variations across drivers. For example, the number of overtaking maneuvers is likely to vary between participants due to differences in driving styles but should be similar across conditions per participant. Our independent variable is the used assistant system with the levels baseline driving without assistance (BL) and driving with ALD.

We define the start of a lane change maneuver based on the course of the lateral position as depicted in Figure 5.18: the last low point before entering the target lane is the start for a leftward lane change, while the last high point is the start for a rightward lane change. In both cases, the end is defined as the moment, when the car enters the target lane.

We measured the gap sizes and the ratio of maneuvers that ended in an unsafe distance to another car as dependent variables regarding driving behavior. The ratio is the number of unsafe maneuvers per total number of maneuvers per participant, condition, and direction. We consider two thresholds to define an unsafe maneuver: *1.8s*, based on the German "half of the speed indicator," similar to the common two-second-rule for good weather conditions; and *0.9s*, based on the minimum distance required by German regulation [Bun17].

To investigate H2 and H3, we measured glance duration, location probability, and frequency as discussed in Section 2.5.2. We defined four AOIs for our analysis: the *front* area around the center of the street, the *dashboard*, and the *left* and *right* areas around the side-view mirrors, including the corresponding ALD. Finnegan and Green [PP90] suggest that a visual search starts about 6.6s before a lane change, based on a literature review. Similarly, Salvucci and Liu observed that drivers started to shift their gaze away from the start lane at about 5s before the lane change [SL02]. Therefore, we decided to include a maximum of 5s before the start of the maneuver in our gaze behavior analysis, or, if the last maneuver ended less than 5s before the current maneuver, at most the complete time since the end of the last maneuver. As depicted in Figure 5.18, the gaze behavior analysis lasts from at most 5s before the start of a maneuver to the end of the maneuver.

We measure user experience of the ALD based LCDAS with a UEQ to be able to compare it to later iterations of the design.

5.3.2.5 Procedure

The experiment took place in our driving simulator with controlled ambient lighting levels and a temperature of 22°C. After introducing the participants to the experiment and collecting demographic data, we equipped them with the eye tracker glasses and started the calibration.

The first driving session was divided into a baseline drive without a light pattern and driving with the ALD. Each session took at least five minutes and served as a training. We did not consider data from these training sessions for the later analysis. After a short break, the test drives were started. The ALD condition followed the BL condition. In each driving session, the experimenter asked the participant to stop the car after ten maneuvers per direction were completed or when at most ten minutes passed. This limit resulted in a mean of 8.8 (SD: 1.5) maneuvers per direction and condition and a mean driving duration of 6:33min (SD: 1:09min) per condition. After the simulated car came to a full stop, the experimenter stopped the simulation. We chose this approach to reduce the risk of disorientation and simulator sickness by breaking the immersion too suddenly. We added a short break between conditions to check the calibration of the eye tracker and reset the driving simulation. After the driving scenarios, participants were asked to fill in the UEQ.

5.3.2.6 Participants

Twenty people (eight female) with normal vision and a valid driving license participated in the experiment. The median age was 25 years (IQR: 6), the median years of possessing a driving license were 7 (IQR: 5.25).

Measure	***Dir.***	***Cond.***	***Mdn***	***IQR***	CI_{low}	CI_{high}	***N***
Duration (s)	Leftw.	BL	3.80	1.87	3.52	4.02	172
		ALD	3.78	2.40	3.42	4.20	181
	Rightw.	BL	3.38	2.08	3.12	3.58	172
		ALD	3.63	2.08	3.32	4.03	181
Speed (m/s)	Leftw.	BL	31.29	4.53	30.44	32.00	172
		ALD	31.44	4.01	30.85	31.92	181
	Rightw.	BL	33.07	4.72	32.05	33.76	172
		ALD	32.52	4.27	32.07	33.20	181
Accel. (m/s^2)	Leftw.	BL	0.09	0.73	0.02	0.21	172
		ALD	0.13	0.49	0.08	0.21	181
	Rightw.	BL	- 0.03	0.47	- 0.09	0.02	172
		ALD	- 0.04	0.39	- 0.09	0.02	181

Table 5.4: Overall medians with IQR and bootstrapped 95% CIs for durations of the maneuvers, speed at the end of the maneuver, and acceleration during the maneuver. N is the number of maneuvers.

5.3.3 Results

We observed 353 leftward and rightward maneuvers from 20 participants. 172 maneuvers were executed in the BL condition, 181 in the ALD condition. The median number of lane change maneuvers per direction and subject is 9 in both conditions with an IQR of 1.25 for baseline and 2 for ALD. Also, a mean of 83.3% (SD: 4.3%) of the pupil positions per subject and condition are valid and can be assigned to one of the AOIs. We aggregated the data by using the median per direction, condition, and subject, leaving us with 80 data points (2x2x20) per measurement for the analysis.

The data were analyzed using R 3.3.3 [R C17]. Visual inspection with Q-Q plots and Shapiro-Wilk tests showed that most data were not normally distributed: neither the values per condition nor the differences between conditions. Hence, we used non-parametric tests for the data analysis and hence report median values (Mdn) along with the interquartile range (IQR), and 95% bootstrapped confidence intervals (95% CI) in this section. The CIs were calculated using the bootstrap percentile interval approximation with 2000 replicates from the “boost” package [CR]. We used exact Wilcoxon-Pratt signed-rank tests using the “coin” package [HHvZ08] to test the significance of our effects. Effect sizes are given as r and extracted from the Z-value of the Wilcoxon-test: $r = Z/\sqrt{N_1 + N_2}$. The medians of the differences are given for significant effects. In contrast to the difference of the medians, it is defined as the median of the pairwise differences between the compared conditions.

	Target	Cond.	Mdn	IQR	CI_{low}	CI_{high}	N
Leftwards	Front	BL	1.828	0.900	1.287	2.086	20
		ALD	1.679	0.620	1.375	1.976	20
	Front L.	BL	1.247	0.811	0.925	1.451	19
		ALD	1.236	0.846	0.927	1.745	19
	Rear L.	BL	3.530	1.399	2.606	3.872	20
		ALD	2.774	1.311	2.220	3.291	20
Rightwards	Front	BL	3.063	2.145	1.945	4.090	17
		ALD	3.312	1.452	2.816	4.120	18
	Front R.	BL	4.328	1.883	3.310	5.028	20
		ALD	4.124	1.375	3.607	4.697	20
	Rear R.	BL	**1.284**	0.763	1.093	1.747	20
		ALD	**1.646**	0.488	1.415	1.802	20

Table 5.5: Median gap sizes with IQR and bootstrapped 95% CIs. N is the number of measures after the median-filter. The gap towards the rear right vehicle increased significantly when using the ALD.

The Average Lane Change Maneuver

Descriptive statistics for speed, duration, and acceleration are presented in Table 5.4. No difference between the conditions was significant. Drivers accelerated for leftward lane changes and slightly decreased the speed for rightward lane changes. The result is a higher speed at the completion of a leftward lane change. On average, leftward lane changes took longer than rightward lane changes.

Gap Sizes

We measured gap sizes to the lead vehicle, the preceding vehicle on the target lane and the rear vehicle on the target lane when entering the lane. The gap sizes were analyzed for each target vehicle individually. Maneuvers without a target vehicle were excluded. Afterwards, the data were aggregated by selecting the median gap size per target vehicle, condition, and subject. Descriptive statistics are summarized in Table 5.5. With a median gap size of less than two seconds, the gaps to the forward vehicle, as well as the front-left vehicle at leftward lane changes can be considered as unsafe in both conditions. When drivers are changing rightwards, the gap sizes to the rear-right vehicle are not safe.

The effect of using ALD on gap sizes in leftward lane changes was neither significant for gaps to the front ($Z = -0.26$, $p = 0.81$), to the front-left ($Z = 0.56$, $p = 0.59$) nor to the rear-left ($Z = 0.93$, $p = 0.37$). Similarly, we did not observe a significant effect for rightward maneuvers on gaps to the front ($Z = -1.42$, $p = 0.17$), or front-right vehicles ($Z = 0.41$, $p = 0.70$). However, the gaps to rear-right vehicles increased significantly

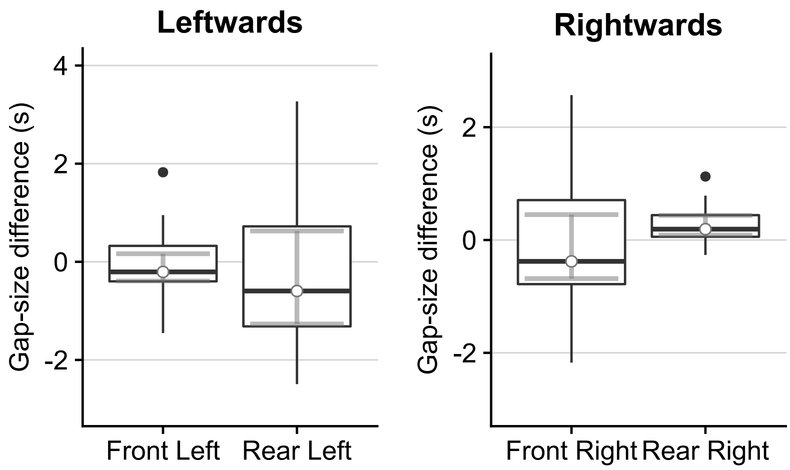


Figure 5.19: Boxplots (black) and bootstrapped 95% CIs for the medians of differences (red) between ALD and BL condition. The gap sizes to the rear right vehicle in rightwards lane change maneuvers are significantly bigger with ALD.

	Thr.	***Cond.***	***Mdn***	***IQR***	CI_{low}	CI_{high}	***N***	***p***
Leftwards	1.8s	BL	79%	30%	71%	100%	20	.75
		ALD	88%	10%	80%	89%	20	
	0.9s	BL	50%	37%	21%	53%	20	.09
		ALD	30%	34%	17%	41%	20	
Rightwards	1.8s	BL	78%	46%	58%	100%	20	.29
		ALD	73%	36%	59%	89%	20	
	0.9s	BL	**11%**	38%	0%	35%	20	$< .01$
		ALD	**0%**	11%	0%	10%	20	

Table 5.6: Ratio of accepted unsafe gaps to any relevant vehicle at a given threshold (Thr.). The difference is significant for rightward maneuvers at a gap size threshold of 0.9s.

with ALD ($Z = -3.10$, $p < 0.01$, $r = -0.35$). The median of the differences per subject is 0.19s (95% CI: [0.09, 0.43]) as depicted in Figure 5.19.

Unsafe Maneuvers

We considered the gaps to the leading vehicle, and the next front and rear vehicle on the target lane. Table 5.6 summarizes the ratio of unsafe maneuvers per participant. We did not observe a significant effect at the 1.8s threshold. However, the ratio of violations of the 0.9s gap to all relevant cars is significantly lower with ALD ($Z = 2.67$, $p < 0.01$, $r = 0.30$). The median of differences is 0% with a 95% CI of [−12%, 0%].

	AOI	Cond.	Mdn	IQR	CI_{low}	CI_{high}	N
Leftwards	Forward Road	BL	**3.71**	0.82	3.41	4.09	20
		ALD	**4.20**	1.58	3.84	4.96	20
	Left Mirror	BL	1.09	0.42	0.85	1.24	20
		ALD	1.11	0.48	0.89	1.29	20
Rightwards	Forward Road	BL	**3.24**	0.95	2.92	3.65	20
		ALD	**4.49**	0.79	4.08	4.79	20
	Right Mirror	BL	1.14	0.55	0.92	1.30	20
		ALD	0.79	1.43	0.00	1.34	20

Table 5.7: Median cumulative glance durations in seconds per participant and condition (Cond.). Participants glanced significantly longer towards the forward area.

	AOI	Cond.	Mdn	IQR	CI_{low}	CI_{high}	N
Leftwards	Forward Road	BL	1.31	0.40	1.13	1.48	20
		ALD	1.56	0.59	1.19	1.72	20
	Left Mirror	BL	0.72	0.17	0.63	0.76	20
		ALD	0.68	0.17	0.60	0.75	20
Rightwards	Forward Road	BL	**1.40**	0.48	1.22	1.62	20
		ALD	**1.86**	1.69	1.52	3.04	20
	Right Mirror	BL	**1.06**	0.46	0.82	1.23	20
		ALD	**0.71**	1.07	0.00	1.05	20

Table 5.8: Median glance durations in seconds per area of interest (AOI), participant, and condition (Cond.). The medians of significantly different values are highlighted in bold.

Cumulative Glance Durations per Maneuver

We derived the glance durations as described in Section 2.5.2. We aggregated the individual gazes into cumulative glance time per AOI and maneuver. We then selected the median time per participant and condition for further analysis. The descriptive statistics for the relevant AOIs are summarized in Table 5.7. The median durations for the omitted AOIs are 0.

We observed significant effects for the cumulative gaze duration towards the forward road for both directions, but no effects for the gaze durations at mirrors. For leftward maneuvers, participants looked longer towards the front ($Z = -2.87$, $p < 0.01$, $r = -0.32$) with a median in the differences of 0.5s (95% CI= $[0.15, 0.77]$). The effect is stronger for rightward maneuvers ($Z = -3.77$, $p < 0.001$, $r = -0.42$) with a median in the differences of 1.1s (95% CI= $[0.50, 1.32]$).

	AOI	*Cond.*	*Mdn*	*IQR*	CI_{low}	CI_{high}	*N*
Leftwards	Forward Road	BL	73%	11%	69%	76%	20
		ALD	74%	11%	70%	79%	20
	Left Mirror	BL	21%	11%	16%	26%	20
		ALD	21%	12%	13%	24%	20
Rightwards	Forward Road	BL	**72%**	11%	66%	75%	20
		ALD	**78%**	22%	73%	88%	20
	Right Mirror	BL	**24%**	10%	19%	27%	20
		ALD	**14%**	17%	7%	21%	20

Table 5.9: Median glance location probabilities in percent per AOI, participant, and condition. The medians of significantly different values are highlighted in bold.

Glance Durations per Glance

We aggregated all maneuvers by selecting the median duration per AOI, maneuver, and participant. Table 5.8 summarizes the descriptive statistics. We did not observe significant effects on forward glance durations for leftward lane changes at $p < 0.05$. For rightward lane changes, ALD increased the glance durations significantly ($Z = -2.86$, $p < 0.01$, $r = -0.32$) with a median in the differences of 0.48s (95% CI= $[0.04, 1.44]$). The glance duration towards the right mirror decreased significantly ($Z = 2.28$, $p < 0.05$, $r = 0.26$) with a median in the differences of -0.1s (95% CI= $[-0.7, 0]$).

Glance Location Probability

The glance location probability was aggregated per participant and condition and is summarized in Table 5.9. It does not differ significantly for leftward maneuvers. However, before and during rightward maneuvers, participants looked significantly more likely towards the forward area with ALD ($Z = -3.06$, $p < 0.01$, $r = -0.34$) with a median of the differences of 3% (95% CI: $[1\%, 14\%]$). They looked significantly less likely towards the right mirror with ALD ($Z = 2.39$, $p < 0.05$, $r = 0.27$) with a median of the differences of -5% (95% CI: $[-13\%, -1\%]$).

Glance Frequency

The glance frequency was aggregated per participant and condition and is summarized in Table 5.10. The measures for leftward maneuvers did not differ significantly. However, the frequency decreased for rightward maneuvers towards the forward AOI ($Z = 2.95$, $p < 0.01$, $r = 0.33$) and the right AOI ($Z = 3.02$, $p < 0.01$, $r = 0.34$). The median of the decreases per participant is 0.08 glances per second (95% CI: $[0.05, 0.12]$) for the front AOI and 0.05 (95% CI: $[0.03, 0.08]$) for the right AOI.

	AOI	***Cond.***	***Mdn***	***IQR***	***CI_{low}***	***CI_{high}***	***N***
Leftwards	Forward Road	BL	0.46	0.10	0.41	0.49	20
		ALD	0.41	0.09	0.38	0.46	20
	Left Mirror	BL	0.26	0.13	0.21	0.33	20
		ALD	0.24	0.11	0.19	0.28	20
Rightwards	Forward Road	BL	**0.41**	0.07	0.38	0.44	20
		ALD	**0.33**	0.12	0.27	0.38	20
	Right Mirror	BL	**0.19**	0.07	0.16	0.22	20
		ALD	**0.13**	0.12	0.06	0.16	20

Table 5.10: Median glance frequencies in glances per second per AOI, participant, and condition. The effects are significant for both relevant AOIs during rightward maneuvers.

User Experience

The UEQ consists of different scales regarding user experience, each ranging from −3 (horribly bad) to 3 (extremely good). It further provides a benchmark to compare the results to previous studies. We analyzed the UEQ data with the provided analysis tool [LHS08]. The attractiveness was rated with a mean of 1.78 (SD: 0.76), perspicuity with 2.14 (SD: 0.75), efficiency with 1.75 (SD: 0.73), dependability with 1.63 (SD: 0.70), stimulation with 1.43 (SD: 0.86), and novelty with 1.35 (SD: 0.91). Looking into the benchmark, attractiveness and perspicuity were excellent, i.e., in the range of the top ten percent of the results. The other measures are good, i.e., within the top 25%.

5.3.4 Discussion

The purpose of this experiment was to evaluate if glance behavior is affected by the use of an ALD based LCDAS (RQ3, H2-H3). Furthermore, we expected to observe further evidence that using an ALD based LCDAS improves the driver's assessment of safe gap sizes (RQ2, H1).

Most differences for leftward maneuvers are not significant. Only the cumulative glances towards the front AOI increased significantly when using ALD, partially supporting H2. For rightward lane changes, the results support our hypotheses. The gaps towards rear right vehicles increase which results in fewer accepted risky gaps below 0.9s (H1). At the same time, the glance duration and location probability increase towards the front and decrease to the right area (H2). Also, the glance frequency decreased for the front and right AOIs, supporting H3.

Our results indicate that drivers were able to perceive crucial information from the LCDAS (H1) without changing their focus as long (H2) or as often (H3) as without assistance during rightward lane changes. With regard to RQ1, this behavior change indicates that the ALD is, at least in rightward lane changes, perceived in the periphery.

5.3.5 Summary

This experiment looked into the effects of an ALD on driving performance (RQ2) and gaze behavior (RQ1) during lane changes on the highway. In contrast to the other experiments of this chapter, we did not restrict the participant's control over their vehicle.

For rightward lane changes, the ambient light display (ALD) assists well in the simulated two-lane highway scenario, while the differences were not significant for leftward lane changes, similar to our first experiment (see Section 5.1). Also, the observed gaze behavior suggests that drivers look longer towards the forward traffic and shorter and less often away when using ALD compared to driving without assistance, supporting our assumptions about ambient light mainly addressing peripheral vision (RQ3)

We were not able to observe significant differences for most measures in leftward lane changes. However, as we saw evidence that the rightward lane changes are affected and that leftward lane changes were affected in Section 5.2, we need to investigate RQ3 with much more observations or in a more controlled experiment.

5.4 An ALD Against a Display Requiring Foveal Vision

In Section 5.3, we looked into the question "is ALD mainly perceived with peripheral vision?" (RQ3). The nature of an unrestricted driving scenario may have caused a large variance of the measurements that covered small effects. Hence, this experiment, as presented in [LYHB19, submitted for publication], focuses on the leftward lane changes in predefined scenarios where drivers are typically uncertain about the optimal decision. We investigate the influence of focal icons, called "Faces with Emotional Expressions" (FEE) versus an ALD based cue that does not require focal vision.

Our goal is to compare drivers' gaze behavior induced by foveal icons with ALD based cues to better understand the impact of visual cues during lane changes (RQ3). We expect to see better decision-making with both systems, based on the results from Section 5.2, Section 5.3, and the previous research of Fei Yan et al. [YEBL16]. We derive from the second experiment that we can expect to see fewer focus changes with ALD and more focus to the forward area, compared to FEE and baseline driving. We argue that a display that demands less focused attention while being as effective in assisting the driver would be beneficial as it potentially reduces distraction. Also, this may reduce cognitive load as different resources are used to process the information.

5.4.1 Designs Cues for the LCDAS

In the following, we will summarize the driver uncertainty model, expanding on Section 3.1.2, and present the designs of FEE and the ALD based cues.

5.4.1.1 Driver Uncertainty Model

The model of driver's uncertainty was proposed in [YELB16]. It is based on the collected empirical data in a driving simulator study, where the distance gap and TTC between the subject vehicle and the approaching vehicle on a two-lane German highway were varied. The model of driver uncertainty is selected as a Tree-Augmented Naive (TAN) Bayesian classifier based on the Bayesian Information Criterion (BIC) score [YELB16]. It is a probabilistic model which can infer driver's uncertainty as certain or uncertain during decision-making, based on the traffic information including TTC_A, TTC_B, G_A, G_B [YELB16]. TTC_A (resp. TTC_B) represents the TTC between the subject and the lead vehicle (the approaching and the subject vehicle, resp.), while G_A (resp. G_B) describes the distance gap between the subject and the lead vehicle (the approaching and the subject vehicle, resp.) [YELB16]. The model of driver uncertainty showed an average accuracy of approximately 0.78 in an evaluation.

5.4.1.2 Design of Faces with Emotional Expressions (FEE)

The abstract faces with emotional expressions (FEE) as symbols were developed and evaluated by Yan et al. [YELB17] and influenced driving performance positively. We chose them because faces can be interpreted intuitively and rapidly [War12]. Also, Frischen et al. [FES08] showed that humans could process emotional faces rapidly and with few efforts.

The symbols use colors and emotional expressions. Color describes both, the safety of the gap and driver's uncertainty, whereas emotional expression describes the suggested lane change decision regarding safety [YEBL16]. When the driver is certain in lane change maneuvers that the system considers safe, the transparent color will be used for the symbol to not disrupt drivers during their decision-making (see Figure 5.20, a). The display becomes more salient when a driver is uncertain, or the system assesses the maneuver as unsafe: it turns green if the maneuver is considered safe (see Figure 5.20, b) or red otherwise (see Figure 5.20, c). Emotional expressions suggest changing the lane with "thumb up" (see Figure 5.20, a-b), and suggest staying on the lane with "palms up" (see Figure 5.20, c). The symbols are located next to the approaching vehicle in the left mirror, to minimize the effort of perceiving them.

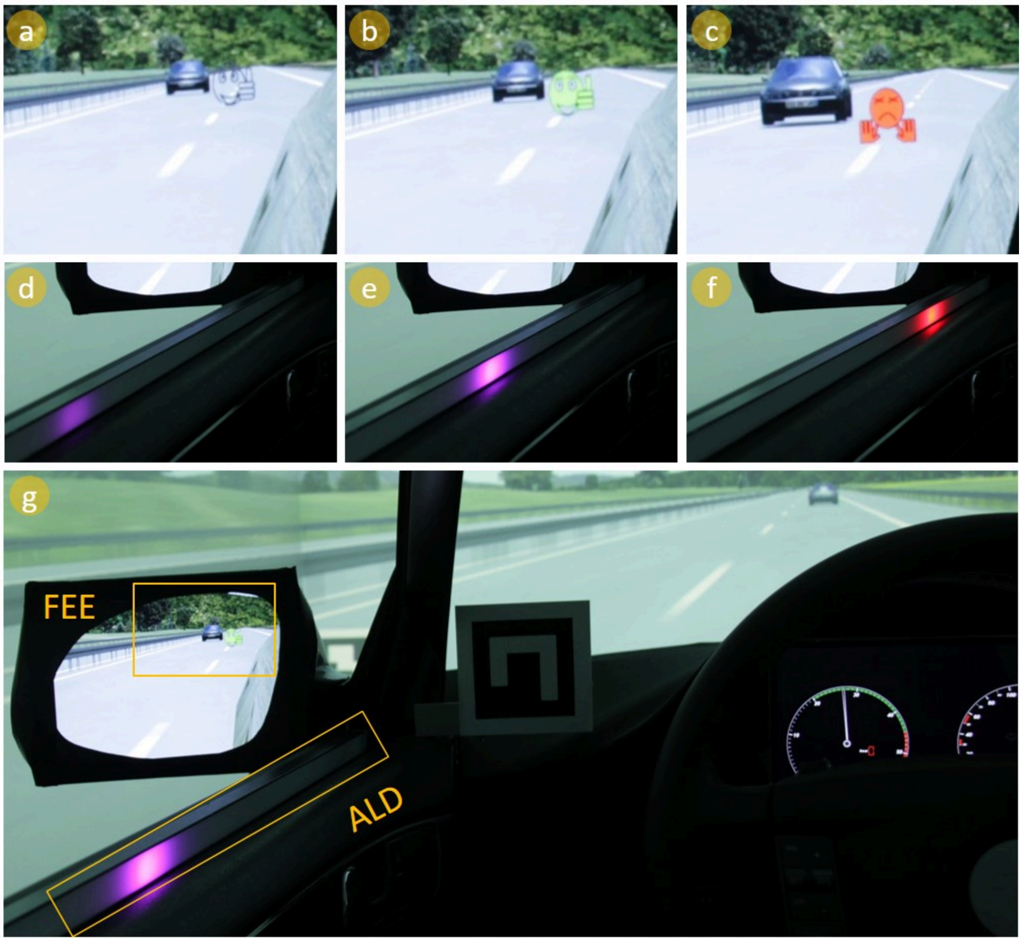


Figure 5.20: Snapshots of the cues in representative lane change situations (a-f) and the positions of FEE and ALD (g). FEE has three states: transparent when the driver is certain, and the maneuver is safe (a); green when the driver is uncertain, and the maneuver is safe (b); red if the maneuver is not safe (c). At the same states, the ALD cue is dark and closer to the B-pillar (d); bright to get the drivers attention (e); close to the A-pillar, red, and bright to dissuade the driver from starting the maneuver (f). In contrast to the depiction in (g), the displays were never combined in the experiment.

5.4.1.3 Design of Ambient Light Display (ALD)

We realized the ALD cue based on the light pattern shown in the second experiment (see Section 5.2): a purple light moves proportionally to the TTC of an approaching rear vehicle. To not increase visual distraction, we designed the ALD pattern to adapt its saliency to the available model of driver uncertainty [YELB16] and only attract attention when necessary. Thus, its brightness is reduced (see Figure 5.20, d) when the driver is certain. When the driver is uncertain, its brightness is highest (see Figure 5.20, e). Also, the color turns from purple to red, if the gap size is considered unsafe (see Figure 5.20, f). The position of the ALD cue is proportional to the TTC of the approaching rear left car and is mapped from B-pillar ($\geq 20s$ TTC) to A-pillar ($\leq 2s$ TTC). At a TTC of less than two seconds, the cue stays at the A-pillar.

The difference to the previous light pattern in Section 5.2 is the used uncertainty model and the added transition to red color. The red color makes the warning level easy to distinguish and combines the benefits of the light patterns from Sections 5.2 and 5.3. The transition is a 500ms color gradient starting in purple at a TTC of 10.35s.

5.4.2 Evaluation in Controlled Driving Simulator Experiment

The experiment in Section 5.4 provided evidence that ALD addresses peripheral vision and has a positive effect on driving performance for rightward lane change maneuvers in a free driving scenario. This experiment focuses on leftward lane changes in demanding lane change situations to complement the first experiment. This experiment does not use free driving but instead generates situations with predefined time gaps that relate to different levels of driver uncertainty. The goal of this experiment is to find more evidence if ALDs are perceived via peripheral vision (RQ3) and have advantages over displays that rely on foveal vision. Therefore, we test ALD against FEE and baseline driving without assistance (BL) in this experiment inside our driving simulator (see Section 3.3).

5.4.2.1 Hypotheses

We hypothesize that the response times when using ALD will be shorter compared to using FEE or BL because the cue is mainly perceived in the periphery and thus the driver does not lose time by switching the focus to the side-view mirror to interpret it (**H1**). Also, we expect to see an increase in glance times and ratios towards the front AOI and a decrease towards the left AOI with ALD, compared to both other conditions because drivers need less time to assess the gap size by looking into the mirrors with the help of ALD (**H2**). If H1 and H2 can be supported, we expect to see a positive effect on the participant's attitude towards ALD. Therefore, user experience may be higher with ALD, compared to FEE (**H3**).

5.4.2.2 Scenario

To be able to observe smaller effects and to specifically focus on situations in which drivers are typically uncertain about which action to take, we created a two-lane highway scenario in which we controlled the distances and speeds of the cars in the simulation. The participant's vehicle starts in the right lane and automatically accelerates to 110km/h. In each trial, two cars appear: a faster car (130km/h) on the left lane and a slower car (100km/h) in front. The initial distances were varied as described further below, and the speed differences were kept constant. The cars are removed after the driver responded by braking or steering and again added with the distances for the next trial after a few seconds.

5.4.2.3 Measurements

We chose a within-subjects design to account for the variance across drivers. The independent variables are the three driving conditions: a baseline condition (BL) with no lane change assistance; a condition in which ALD signals the driver's uncertainty, the rear car's position, and the safety of the gap size (ALD); and a third condition in which FEE was used analogously. We counterbalanced the order of conditions using a Latin Square design.

We use response times as an indicator of driving performance (H1) because it is the typical behavioral indicator [PK14]. Response times are measured as the time between an auditory cue and the driver's steering or braking reaction. Gaze behavior (H2) was measured with the eye tracker as described in Section 2.5.2. To investigate H3, we let the participants rate the subjective quality of both displays with questionnaires. The user experience was measured using a UEQ. In addition, we created four seven-point scales ranging from one statement to its antonym. The additional items were *trustworthiness* ("unreliable" ↔ "trustworthy"), *perceived reaction time* ("slows down reaction" ↔ "speeds up reaction"), *quality of information* ("informs well about traffic" ↔ "informs insufficiently") and *timing of information presentation* ("informs in time" ↔ "informs too late").

5.4.2.4 Procedure

The experimenter gave a brief introduction and collected demographic data. Afterwards, participants drove a training trial without assistance in order to acclimate to the simulator. After the training, the experimenter set up the eye tracker.

The drivers were instructed to wait for the start of a sound and then steer or brake, depending on their assessment of the safety of the maneuver. Driver inputs were recorded but did not affect the car. If the driver input came after the sound, the surrounding cars were removed from the street and prepared for the next trial.

We varied the time to the sound, a 200ms white noise signal, between five and thirteen seconds and manipulated the rear car's initial distance to make the bumper-to-bumper TTC between the rear and the participant's car either 7s, 10s, 11.5s, 12s, or 15s when the sound is triggered. Further, we varied the initial distance of the lead vehicle always to be 7.5s TTC when the sound is triggered. We fixed the speed differences to 5.56m/s for the rear vehicle and -8.33m/s for the lead vehicle. The TTC to the preceding car is always 7.5s at the time of the sound. This distribution of TTC emphasized distances where drivers are known to be uncertain about which actions to take based on our previous studies [YWL15, YELB16]. The participants repeated the driving task 50 times (10 times per target TTC) in a randomized order per condition.

Immediately after using each display, the participants were asked to complete the questionnaire consisting of the UEQ [LHS08] and our additional items.

5.4.2.5 Participants

Twenty-four participants (11 female) took part in this study. They had a mean age of 23.5 years (*SD*: 3.0) and possessed a valid German driver's license for 5.9 years (*SD*: 2.9) on average. Each one drove with an annual mileage between 100*km* and 18,000*km* with an average of 5,000 kilometers per year (*SD*: 5,247). They received €10 each.

5.4.3 Results

The data were analyzed using R 3.3.3 [R C17]. We use non-parametric tests for the data analysis and report median values (Mdn) along with the inter-quartile-range (IQR), and 95% bootstrapped confidence intervals (95% CI), which were calculated using the bootstrap percentile interval approximation with 2000 replicates from the "boost"-package [CR]. We use Friedman rank sum test using the "stats"-package [R C17] to test for significant differences, followed by Wilcoxon-Pratt signed-rank tests with Holm correction of the p-values. We decided to use non-parametric tests after visual inspection with Q-Q plots and Shapiro-Wilk tests did not show a normal distribution for most measures. Effect sizes are given as r and extracted from the Z-value of the Wilcoxon-test. Also, the medians of the differences are presented for significant effects.

We extracted 3,600 data points to measure driving performance: ten points per five target TTCs when the sound is triggered (TTC_{target}) in three conditions for 24 participants. The gaze analysis is summarized in Section 2.5.2. Overall, a mean of 84.1% (SD: 9.2%) of the pupil positions per subject and condition was valid and could be assigned to one of the AOIs. However, we needed to exclude four participants from the gaze analysis due to incomplete data or bad pupil recognition. This exclusion raised the ratio to 86.1% (SD: 5.3%). In total, 3,000 data points regarding gaze behavior from 20 people were analyzed.

Response Times

Figure 5.21 gives an overview of the median response times per TTC at the auditory signal (TTC_{target}). The overall response times were 0.843s in BL condition (95% CI: [0.81, 0.87]), 0.867s with FEE (95% CI: [0.85,0.90]), and 0.817s with ALD (95% CI= [0.78, 0.85]). The Friedman test did not show a significant effect ($\chi^2(2) = 5.82$, $p = 0.06$). However, the Wilcoxon tests revealed a significant difference between ALD and FEE ($Z = -3.06$, $p_{holm} < 0.01$, $r = -0.20$). The median of differences between ALD and FEE

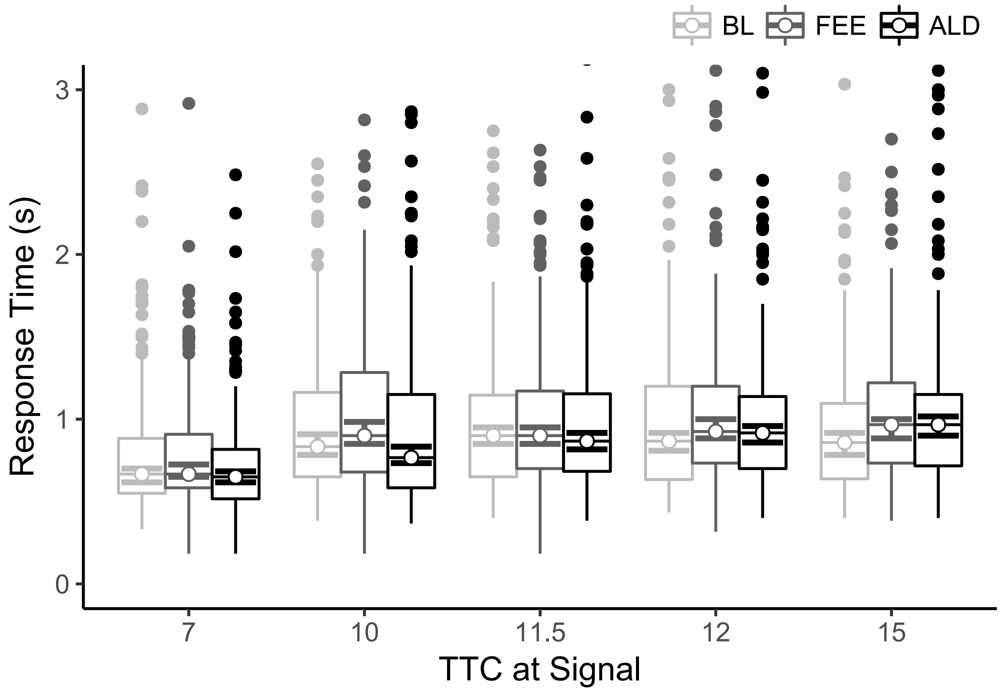


Figure 5.21: Boxplots and bootstrapped 95% confidence intervals for the medians of response times for BL, FEE, and ALD condition at different target TTCs. The response times are overall significantly faster with ALD, compared to FEE.

is 0.05s (95% CI: [0.02, 0.07]), which suggests that response times are faster with the ALD. Friedman tests did not reveal significant effects if the data are analyzed separately per TTC_{target}.

Decisions

We analyzed how the displays affected the decision by calculating the ratio of braking decisions per subject, condition, and TTC_{target}, giving us 120 measures per condition. The overall difference is not significant ($\chi^2(2) = 4.69$, $p = 0.10$) with median values of 30% braking for baseline driving (95% CI=[20%, 50%]) and 20% for FEE as well as ALD (both 95% CI=[10%, 50%]).

Figure 5.22 shows that the displays affected the decisions differently per TTC_{target}. Specifically, the ratio differed clearly for $TTC_{target} = 10s$ ($\chi^2(2) = 10.39$, $p < 0.01$) and $TTC_{target} = 11.5s$ ($\chi^2(2) = 15.69$, $p < 0.01$). Based on our model, the uncertainty is highest for these TTCs, and both displays switch to recommending braking between 11.5s and 10s TTC.

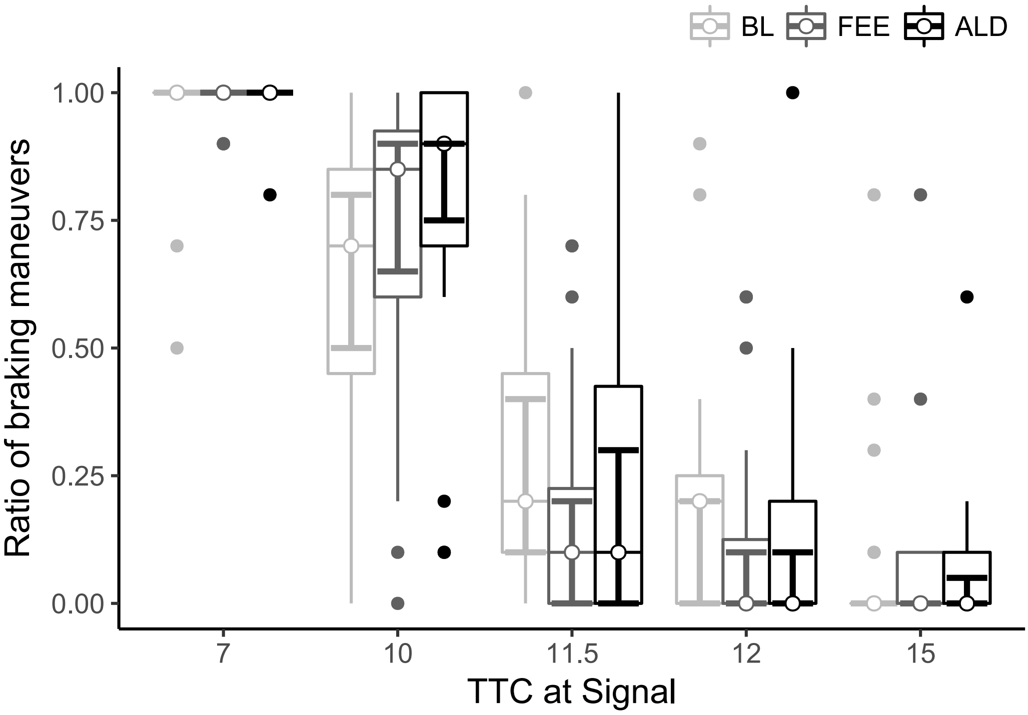


Figure 5.22: Boxplots and bootstrapped 95% confidence intervals for the ratios of braking maneuvers BL, FEE, and ALD condition at different target TTCs.

At $TTC_{target} = 10s$, participants braked more frequent with ALD (Mdn = 90%, 95% CI=[75%, 90%]), compared to BL (Mdn = 75%, 95% CI=[50%, 85%], $Z = -2.84$, $p_{holm} < 0.01$, $r = -0.41$). The median of differences between ALD and BL is 10% (95% CI=[10%, 30%]). The difference between FEE (Mdn = 85%, 95% CI=[60%, 90%]) and BL ($Z = -2.07$, $p_{holm} = 0.07$), as well as the differences between FEE and ALD ($Z = 1.69$, $p_{holm} = 0.09$) are not significant.

At $TTC_{target} = 11.5s$, participants braked less often with FEE (Mdn = 10%, 95% CI=[0%, 20%]), compared to BL (Mdn = 25%, 95% CI: [10%, 40%], $Z = 3.65$, $p_{holm} < 0.01$, $r = 0.53$). The median of differences between BL and FEE is 10% (95% CI: [0%, 20%]). Using ALD (Mdn = 10%, 95% CI: [5%, 30%]) also lowered the ratio significantly ($Z = 2.41$, $p_{holm} < 0.05, r = 0.35$) with a median of differences to BL of 0% (95% CI: [0%, 10%]). The difference between ALD and FEE was not significant ($Z = 1.91$, $p_{holm} = 0.06$).

AOI	*Cond.*	*Mdn*	*IQR*	CI_{low}	CI_{high}	*N*
Forward Road	BL	0.23	0.37	0.10	0.31	100
	ALD	0.28	0.45	0.16	0.36	100
	FEE	0.28	0.37	0.22	0.36	100
Left Mirror	BL	0.38	0.67	0.23	0.52	100
	ALD	0.40	0.64	0.00	0.48	100
	FEE	0.39	0.63	0.25	0.49	100

Table 5.11: Median glance durations in seconds per AOI, participant, and condition (Cond.). The durations for the right, dashboard and rear-view mirror AOIs are 0s with 95% CIs of [0, 0] across conditions.

Performance

Participants could not change the velocity of their car or steer in this experiment. Thus, the gaps and safety violations depend only on the driver's decision and response time. However, these measures may relate the results better to the other experiments of this chapter. The resulting median difference in time gaps between FEE and ALD is 9ms (95% CI=[3ms, 12ms]) and the resulting median difference for the ratio of unsafe gaps with a threshold of 1.8s is 10% (95% CI=[10%, 25%]) for the target TTC of 10s, but not significantly different across TTCs or for any other TTC.

Total Glance Time off Road-Scene Ahead

The time off road-scene ahead is defined as the cumulative glance durations for glances to all AOIs other than the forward AOI. The median time is 0.60s ($IQR = 0.44, 95\%\ CI$: $[0.54, 0.70]$) for BL, 0.59s ($IQR = 0.41, 95\%\ CI$: $[0.50, 0.64]$) for ALD, and 0.57s ($IQR = 0.41, 95\%\ CI$: $[0.52, 0.69]$) for FEE. The differences between them are significant ($\chi^2(2) = 8.54$, $p < 0.05$). The participants looked significantly shorter away from the front with ALD, compared to BL ($Z = 2.61$, $p_{holm} < 0.05$, $r = 0.18$) and FEE ($Z = 2.91$, $p_{holm} < 0.05$, $r = 0.21$). The median difference per participant is 0.02s between ALD and BL (95% CI: [0, 0.10]) and 0.04s between ALD and FEE (95% CI: [0.01, 0.08]).

Glance Durations

Descriptive statistics for the glance durations are summarized in Table 5.11. Glance durations for the right, dashboard or rear-view mirror AOI were 0s with 95% CIs of [0, 0] across conditions. Glance durations did not differ significantly across conditions for the forward AOI ($\chi^2(2) = 3.11$, $p = 0.21$) or left AOI ($\chi^2(2) = 5.85$, $p = 0.05$).

AOI	***Cond.***	***Mdn***	***IQR***	CI_{low}	CI_{high}	***N***
Forward Road	BL	**28%**	26%	22%	32%	100
	ALD	**37%**	34%	29%	43%	100
	FEE	32%	33%	25%	38%	100
Left Mirror	BL	45%	40%	34%	55%	100
	ALD	44%	53%	28%	54%	100
	FEE	44%	37%	37%	50%	100
Rear-View Mirror	BL	**8%**	33%	4%	19%	100
	ALD	**7%**	22%	3%	10%	100
	FEE	**6%**	23%	1%	12%	100

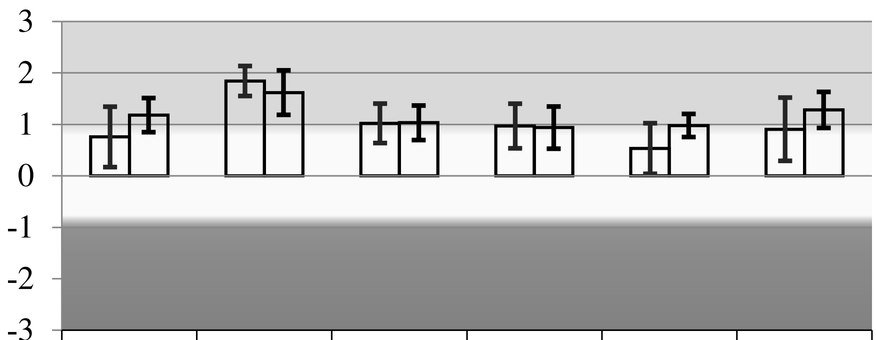
Table 5.12: Median glance location probabilities per AOI, participant, and condition. The probabilities for the right and dashboard AOIs are 0% with 95% CIs of [0%, 0%] across conditions. Significantly different medians are highlighted in bold.

AOI	***Cond.***	***Mdn***	***IQR***	CI_{low}	CI_{high}	***N***
Forward Road	BL	0.63	0.51	0.55	0.74	100
	ALD	0.74	0.57	0.65	0.86	100
	FEE	0.76	0.51	0.65	0.86	100
Left Mirror	BL	**0.72**	0.47	0.68	0.82	100
	ALD	**0.61**	0.65	0.49	0.78	100
	FEE	0.71	0.36	0.64	0.79	100
Rear-View Mirror	BL	0.20	0.66	0.14	0.49	100
	ALD	0.17	0.54	0.11	0.27	100
	FEE	0.17	0.56	0.07	0.32	100

Table 5.13: Median glance frequencies in glances per second. The frequencies for the right and dashboard AOIs are 0 with 95% CIs of [0, 0] across conditions. Significantly different medians are highlighted in bold.

Glance Location Probability

As summarized in Table 5.12, the left and forward AOIs received the highest glance location probabilities. The probabilities of forward glances differed significantly between conditions ($\chi^2(2) = 10.08$, $p < 0.01$). The Wilcoxon tests showed that the probability is significantly higher with ALD compared to BL ($Z = -3.37$, $p_{holm} < 0.01$, $r = -0.24$), with a median of differences of 4% (95% CI: [2%, 10%]). The differences for the left AOIs were not significant ($\chi^2(2) = 5.04$, $p = 0.08$). The glance location probabilities towards the rear-view mirror differed significantly ($\chi^2(2) = 12.47$, $p < 0.01$). The probability was higher with BL, compared to ALD ($Z = 3.39$, $p_{holm} < 0.01$, $r = 0.24$) or FEE



	Attrac-tiveness	Per-spicuity	Effi-ciency	Depend-ability	Stimu-lation	Novelty
FEE	0.8	1.8	1.0	1.0	0.5	0.9
ALD	1.2	1.6	1.0	0.9	1.0	1.3

Figure 5.23: Mean ratings of the User Experience Questionnaire (UEQ) with 95% confidence intervals. The results are scaled from -3 (the most negative answer) to +3 (the most positive answer).

($Z = 3.10$, $p_{holm} < 0.01$, $r = 0.22$). The median of the differences is 1% between BL and ALD (95% CI: [0%, 5%]) and 2% between BL and FEE (95% CI: [0%, 4%]).

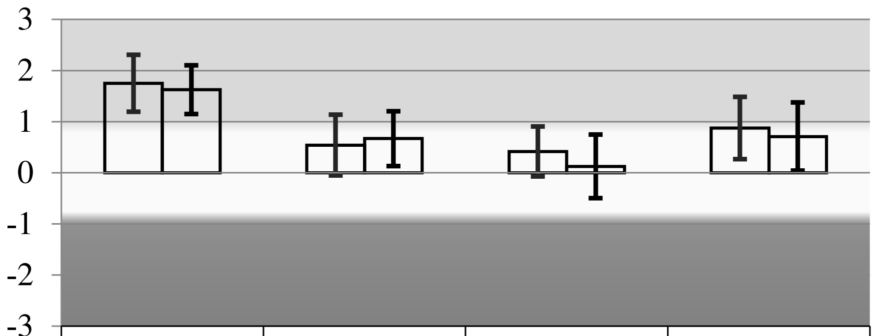
Glance Frequency

The glance frequency is summarized in Table 5.13. We observed no effect for the forward AOI ($\chi^2(2) = 3.92$, $p = 0.14$). However, the difference for the left AOI is significant ($\chi^2(2) = 7.17$, $p < 0.05$). Wilcoxon tests revealed that the participants glance less often to the left AOI in the ALD condition, compared to BL condition ($Z = 2.72$, $p_{holm} < 0.05$, $r = 0.19$). The median in differences is 0.08 fewer glances per second (95% CI: [0, 0.15]). The frequencies also differ significantly for the rear-view mirror ($\chi^2(2) = 7.27$, $p < 0.05$). However, pairwise Wilcoxon tests did not reveal effects.

User Experience

The UEQ data were analyzed using the provided analysis tool (see [LHS08]). As shown in Figure 5.23, both displays received positive feedback for each UEQ scale, but they did not differ significantly. The hedonic qualities (perspicuity, efficiency, and dependability) are positively rated with a mean of 1.13 (SD: 0.61) for ALD and 0.72 (SD: 1.32) for FEE. The pragmatic qualities (stimulation and novelty) are also positive for both displays with a mean of 1.19 (SD: 0.88) for ALD and 1.28 (SD: 0.76) for FEE.

Looking into the benchmark, attractiveness is below average (worse than 50%) for FEE, but above average (better than 50%) for ALD. Novelty scores above average with FEE, but good (better than 75%) with ALD. Both displays score similarly for perspicuity (good), efficiency (above average), dependability, and stimulation (both below average).



	Reliability	Faster Reactions	Informs Well	Informs in Time
FEE	1.8	0.5	0.4	0.9
ALD	1.6	0.7	0.1	0.7

Figure 5.24: Mean ratings of our scales with 95% confidence intervals. Answers to our questions ranged from -3 (the most negative answer) to +3 (the most positive answer).

As shown in Figure 5.24, the ratings for our additional scales were not significantly different between the displays. On the reliability scale, both displays were rated as somewhat trustworthy with a mean of 1.75 (SD: 1.39) for FEE and 1.63 (SD: 1.19) for ALD. The other scales tend to the positive side. Both displays are more perceived to speed up the reaction time than to slow it down with a mean of 0.54 (SD: 1.49) for FEE and 0.67 (SD: 1.34) for ALD. The quality of the information is rated worst for both displays and on average between informing well and informing insufficiently with a mean of 0.42 (SD: 1.22) for FEE and 0.13 (SD: 1.56) for ALD. A mean of 0.88 (SD: 1.52) for FEE and 0.71 (SD: 1.67) for the timing suggests that participants perceived the timing for the presentation of the information as adequate.

5.4.4 Discussion

We could show that using the ALD has the intended effect on decision-making as drivers braked more often at close gaps (10s TTC or 1.5s time gap) compared to the baseline drive and less often at safe gaps (11.5s TTC or 1.8s time gap). FEE affected the decision for safe gaps, but not for close gaps.

The results also show that drivers respond faster with ALD compared to FEE, supporting H1. However, the effect is small and translates only to a 0.009s bigger time gap towards the rear left vehicle on average, compared to FEE.

Gaze durations and the location probabilities do not differ significantly between the displays. However, participants were more likely to look towards the front with ALD than without assistance, while FEE did not affect this measure. Also, the cumulative glance time away from the forward road scene is lower with ALD, compared to FEE. These results show a tendency of ALD being perceived with less focused vision than FEE, but not as clear as expected, partially supporting H2. The reduced glance frequency to the rear-view mirror for both displays can be explained by the fact that no additional information is presented there, comapred to the left AOI.

H3 is not supported: the differences in the UEQ scores and our additional scores did not differ significantly between ALD and FEE. Still, both displays were rated positively overall. ALD may be improved in the pragmatic qualities, such as clarity, e.g., by giving distinct suggestions, while the FEE can be improved by making it more enjoyable.

One limitation of this experiment is that we controlled the speed of all vehicles and did not allow the driver to accelerate, decelerate or change the lateral position. Also, the trials were reset after each initiation of a steering or braking maneuver, what differs to a natural driving experience. Furthermore, we only analyzed driver behavior between the start of the sound and a corresponding reaction, which creates much smaller time frames that mainly contain the last update of the assessment of the current situation and not the whole decision-making process. Although we expect that the effects can be found without these limitations, they may still have affected the participants' behavior. Therefore, future experiments need to be designed without these limitations to validate the effects.

Overall, our results suggest that the ALD tends to help to make good lane change decisions in line with the results of Sections 5.2 and 5.3 (RQ2). With regard to RQ3, we showed that an ALD might assist drivers at least as good as a display that requires focused attention.

5.5 Summary

This chapter presented four experiments that evaluated six light patterns for an LCDAS against at least baseline driving without assistance. In the first experiment, both patterns are derived from the design workshop presented in Section 4.5 and warning levels based on TTCs from ISO 17387 [ISO08]. Both patterns did not outperform baseline driving. Further, the pattern that was designed to be close to state-of-the-art blind spot notification systems seemed to confuse drivers and made them take fewer safe decisions.

As insufficient thresholds may have caused the results of the first experiment for the warning levels, we refined the continuous light pattern into two patterns. Both are again moving from the B-pillar towards the A-pillar when a rear left car approaches. However, both start much earlier to display the car and do not use colors to indicate a warning level. Further, the "adaptive" pattern adapts its brightness to the uncertainty of a driver to be salient when the system assesses the driver to be uncertain. We learned that adapting the light to the driver's uncertainty can lead to quicker responses and fewer unsafe maneuvers.

In the first two experiments, we artificially controlled the situation before a lane change. Hence, we were interested in the effects of an ALD during more natural driving. It is the focus of the third experiment in which we also looked into the gaze behavior to investigate RQ3. We developed a new light pattern that does not adapt to the TTC, but to the time gap, and did not change its location, but its color to indicate the current safety. With this pattern, participants looked longer towards the front and less often accepted risky gaps when changing to the right lane.

We realized the fourth experiment to complement our earlier gaze behavior results. In this experiment, we reiterated on the adaptive pattern, adding a red warning level, and compared it to a system that required focused attention. In contrast to the third experiment, we limited the drivers' control over the car and asked them to only overtake or brake after an auditory signal. We observed that drivers reacted slightly faster with ALD and followed the suggestions of the displays. Also, drivers looked shorter and less often away from the forward area when using ALD.

5.5.1 Contributions to RQ1 – Investigating Parameters for Ambient Light

The experiments did not focus on RQ1. However, we tested two encodings: changing the color depending on the safety assessment and moving from B- to A-pillar to indicate an approaching vehicle.

We developed light patterns with color encoding for the first and third experiment. However, it only had a positive effect in the third experiment in which its safety levels were based on the time gap rather than the TTC. Moving patterns were used in three of the four experiments. While the participants' feedback was positive in general, this way to encode the distance only had a positive impact when combined with adapting the brightness based on driver uncertainty.

We derive from the interviews and UEQ results that this encoding is less intuitive than using colors with a traffic-light metaphor, which is its the main drawback. Combining a spatial and a color encoding for the same measure (e.g., time gap or TTC) was estimated as redundant and possibly confusing.

It seems to be beneficial to encode if the gap is safe or not, e.g., by displaying safety levels with red and green, and to get the drivers' attention when they are uncertain, e.g., by increasing the brightness. While participants liked it when the light cue's position corresponds with the gap to the other vehicle, other spatial encodings like a growing or shrinking size of the display, as, e.g., discussed in Section 4.5, may be suitable as well. Overall, our combination of a spatial encoding of the gap and a color encoding using red as warning, in addition to adapting the brightness to the uncertainty of the driver (see Section 5.4) worked well, but the best encoding is likely still to be uncovered.

5.5.2 Contributions to RQ2 – Displaying Important Information Effectively

The focus of this chapter lies on the question of what makes ALDs effective when supporting drivers. We chose changing lanes as the scenario to investigate this question because drivers need to assess information from different locations with varying criticalities to decide for a safe maneuver.

Overall, our results indicate that ALDs need to be designed carefully to be effective. While participants often suggested realizing clearly distinguishable safety levels that are encoded in a traffic light metaphor, we only observed an effect for rightward lane changes when implementing the light pattern in this way. On the other hand, spatial encodings were only effective, when combined with an encoding of the driver's uncertainty.

The displays were most effective in situations were drivers are believed to be uncertain about which decision to make. Thus, we argue that the most important aspect of an LCDAS display is to get the driver's attention when needed. Our adaptive patterns showed how this could be achieved by increasing the brightness, and increased driving performance similarly well (in terms of the number of safe decisions) or more (concerning the reaction time) than a comparable display that also adapts to driver uncertainty but requires focused attention.

Overall, most light patterns were effective in improving driving performance, but only to a small degree. However, our drivers were not distracted, and the traffic situations were usually easy to oversee. Considering that ALDs address peripheral vision and thus do not distract cognitive resources that are needed to perceive information with foveal vision, we expect that the effect is more likely to increase in more demanding driving situations than to decrease. However, more research has to be done to examine this assumption.

5.5.3 Contributions to RQ3 – Effects of ALDs on Gaze Behavior

Two of the presented experiments in this chapter investigated if ambient light cues are mainly perceived in the periphery (RQ3), including comparing it to a display that required foveal vision.

In both experiments, we observed that drivers looked longer and more often towards the forward area when using ALDs. The difference to FEE, the display that needs to be perceived via foveal vision, is not as clear. Still, the glance times away from the forward area are lower with ALD, supporting our assumption.

Together with our observations in Section 4.2, we derive that drivers can perceive crucial information from ALDs with peripheral vision.

6 Designs for the Future

During the research for this dissertation, several ideas have been withdrawn, or only looked at superficially. However, some of these works are worth reporting as they show use cases for future ALDs and open up new research directions. This chapter summarizes the projects that investigated future use cases and ideas on how to explore ALDs more efficiently.

In the first part of this chapter, we present two works that investigate new ways of prototyping light patterns. First, using a model sized car that can, e.g., be brought into workshops to demonstrate ideas for light patterns and refine them on the fly during the discussion. Second, a portable light display that can, e.g., be attached into a voluntary participant's car to demonstrate and discuss design ideas in-situ, possibly uncovering issues that were not seen in sketches or prototypes in the lab.

In the second part of this chapter, we present two concepts that are not displaying safety-critical information but showcase use cases for ALDs in future settings. In the first work, we develop four concepts in a small workshop that may help to keep a driver's frustration low. In the second work, we develop a display that indicates the intentions of an automated vehicle to its passengers.

6.1 A Scaled Model Car to Visualize Ambient Light Patterns

When developing and discussing ambient light patterns, we learned that it can be difficult to make designs tangible. Hence, we developed model sized cars. After realizing the first prototype as a demonstrator, shown in Figure 6.1(a), we decided to develop a prototyping tool, called SMALLCAR (Scaled Model for Ambient Light Display Creation and Review) that enables us to easily demonstrate ideas and quickly modify light patterns during discussions, e.g., at design workshops.

In this section, we elaborate on our early results, presented in [SLHB17], and present a working prototype as well as results of two user tests: the first one with developers during design exploration and the second one with a group of drivers evaluating given light patterns. Our results indicate that the prototype helps to better understand and discuss light patterns.

6.1.1 Related Works

In-vehicle light patterns are often implemented and evaluated inside the interior of a real car or a mocked-up interior of a driving simulator. However, developing these prototypes can be expensive, and the environment may not always be available. To reduce these downsides, we propose using a downscaled model car. One of the main advantages is the reduced effort during the design process, which allows more room for improvements during design iterations. Also, the small size makes it mobile and enables users to carry it to, e.g., workshops or discussions.

Model cars have been used to answer research questions or to test the feasibility of an idea. For example, ConceptCar2 [IES14], created by the Fraunhofer Institute for Experimental Software Engineering, can be equipped with sensors and new technologies for testing purposes. Another model was developed at the Freie Universität Berlin. It was used to develop and test a system for automatic lane recognition [Kra14, Lä15, Mai14]. Furthermore, Yu et al. [YKG07] equipped a ride-on car with sensors to test a driver assistance system.

6.1.2 The Design of SMALLCAR

SMALLCAR is meant to aid the viewers' projection of an implemented light pattern onto an actual in-car implementation. Towards this goal, we first extracted requirements from related works. To complement these and to better understand the user's expectations for SMALLCAR, we performed a brainwriting session with five male participants with an age of 22 to 34 years (M: 27, SD: 4.4) of which four had experience in developing ambient light patterns. After writing down their expectations on the project, the most important requirements were identified and discussed.

The summarized results are: the model car should be about ten times smaller than a real car and look plain, neutral, open, and realistic. It should be easily transportable and observable. To realize the light display, RGB LED strips should be attached in a replaceable and expandable way. The displays should also be easily dimmable and diffused.

6.1.3 Implementation

As shown in Figure 6.1, the prototype is built into a remote-controlled plastic model of a four-door car. Its exterior dimensions are 43x20x17cm.

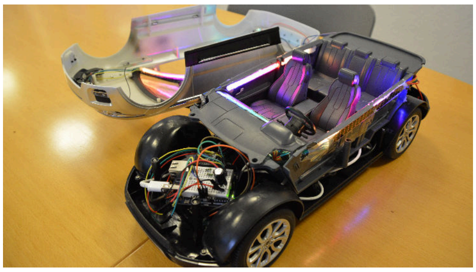
The roof window is detachable and allows observing the interior. An individually controllable RGB LED strip with 144 LED/m has been installed alongside the interior of the car at the height of the bottom edges of the windows, alongside the A-pillar, and around the roof as shown in Figure 6.1(e). It is controlled by an Arduino Yún to which Arduino code can be uploaded wirelessly. A 20Ah battery powers the light display and the Arduino. In addition, we developed a wireless sensor box which can be used to simulate approaching vehicles or map the measured distance to another input. It is equipped with an ultrasonic distance sensor which allows measurements from 2cm up to 2m. The measured data gets processed by an Arduino Uno and is then transmitted to the SMALLCAR via an RF-Transmitter.

(a) First prototype. Here demonstrating the adaptive LCDAS (see Section 5.2)

(b) The sensorbox next to the prototype displaying the currently measured distance.

(c) The model car used for this prototype – a *Range Rover Evoque*, Model no. *DX121030* – next to a regular car.

(d) The interior of the car is realistic enough to enable snapshots from the interior.



(e) The interior of the equipped model car. The Arduino Yún and LED strips are easy to reach and can be maintained or replaced.

(f) An example light pattern: two dynamic lines of light approaching from either side of the LED strip attached inside the dashboard.

Figure 6.1: The model cars equipped with ambient light displays.

To ease the participants into working with SMALLCAR, some common methods such as the communication with the display and changing the brightness or color are already available. For example, a moving light dot pattern is ready for use and can be freely edited to the participants' liking, or used as an example of how to create a custom light pattern.

For example, the light pattern shown in Figure 6.1(f) is a combination of two predefined functions. If an obstacle (e.g., another model car) approaches the sensor box, the light bars move towards each other and the center. Their color transits from white to yellow to alert the driver. This pattern was designed and implemented by two participants of the study mentioned in the next section.

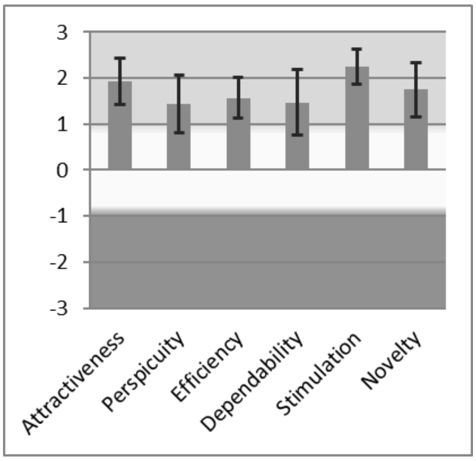
6.1.4 Usability Tests

The goal of this work is to develop a prototyping tool that can be used for designing and evaluating light patterns, before creating more costly implementations. We expect it to generate highly valuable early feedback which may enable developers to reiterate designs before running further experiments. We conducted two experiments with students who were unaffiliated with in-vehicle light patterns to gain insight into these use cases.

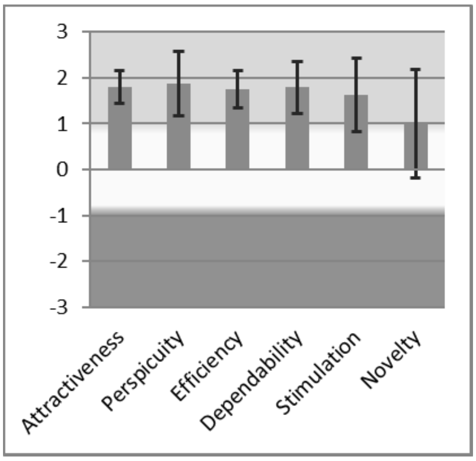
The first experiment is designed to yield information about the viability of using SMALLCAR as a basis for discussion from the developers' point of view. The second experiment aimed at revealing if a light pattern implementation in SMALLCAR helps to understand and experience it and therefore generates better feedback when testing a light pattern design.

6.1.4.1 Using the Prototype for Design Exploration

Seven individuals (1 female) between the age of 22 and 27 took part. They were separated into four groups of one or two people. All participants had between 2 and 10 years of programming experience and owned a driver's license for 4.5 to 8 years. First, the participants were introduced to SMALLCAR and their tasks. We then explained the prototype and code examples in detail and let them develop a light pattern which should warn about lateral collisions in a 15min guided tutorial. Afterwards, the task of each group was to collaboratively design and implement a light pattern on their own for an overtaking maneuver. During this task, the instructor took a passive role by only answering technical questions. Once the allocated time ran out, or they were satisfied with their result, the participants shared their experiences in a semi-structured interview and filled out a UEQ. Each session took about 90min.



(a) UEQ results for the design exploration experiment. “Attractiveness” and “stimulation” were rated highest, “perspicuity” and “dependability” lowest, but still “above average” in the benchmark.



(b) UEQ results for the validation experiment. “Attractiveness” was rated highest, “novelty” lowest, but still “above average” in the benchmark.

Figure 6.2: UEQ results for both experiments.

6.1.4.2 Using the Prototype to Check for Issues

A group of six people (1 female) took part in a 90min session. In the beginning, the participants were briefly introduced to in-vehicle ALDs. Afterwards, the experimenter provided pictures and the corresponding descriptions of the 360° display by Dziennus et al. [DKS16] and our light pattern to support lane change decisions (see Section 5.2). After each, the participants were asked to give feedback about the pattern and suggest improvements. In the second part, our implementations of the respective light patterns in the SMALLCAR were shown, and the participants were asked to give further feedback. Additionally, we asked them if the presented light patterns corresponded to their expectations based on the earlier descriptions. Following up on this, the participants were asked to look for usability issues of the SMALLCAR with the aid of the heuristics of Mankoff et al. [MDH+03]. Afterwards, the participants answered a UEQ.

6.1.5 Results and Discussion

The UEQ results indicate an overall positive reception to the prototype as shown in Figure 6.2. In both experiments, the prototype was rated to be very attractive and stimulating. The efficiency also received a good score in both experiments. “Perspicuity” and “Dependability” were rated lower in the exploration experiment. We argue that this is caused by the need to program the pattern instead of having a more straightforward user interface. The participants in the validation experiments disagreed on how novel the prototype would be which might explain the difference in the average scores.

The discrepancy in hedonic quality may have resulted from the different tasks in each study: whereas the participants of the design exploration study were asked to get creative and work on their interpretation of a light pattern, those of the second study took a passive role by observing, evaluating and discussing.

6.1.5.1 Study Results for Design Exploration

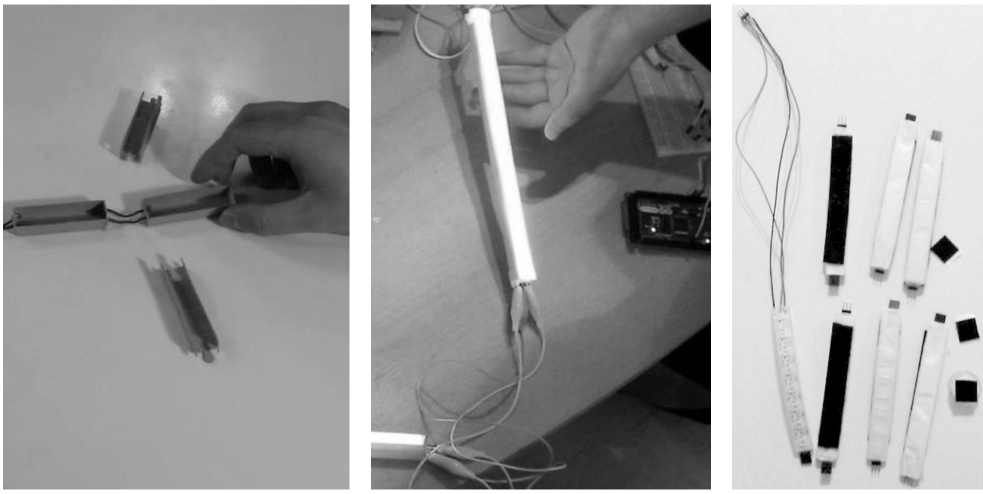
The appearance of SMALLCAR was well-received and labeled as "innovative", "interesting", "intuitive", "convincing", "realistic" and "true to detail". The prototype was deemed as easily transportable while still being large enough to imagine the light pattern inside a real car. The detachable roof allowed easy observation. Unused parts of the light display were not perceived as distracting. The ability to use the model car and the sensor box wirelessly was well-received as it allowed for more freedom during the design process. Accustoming to working with the prototype was "simple", even though the Arduino IDE was deemed as limited in functionality. Participants stated that SMALLCAR supported collaborative working due to the quick implementation of discussed changes to a light pattern. All participants could see themselves using SMALLCAR to demonstrate their patterns in a design session. They were satisfied with their results and believed to be able to create more advanced patterns.

6.1.5.2 Study Results for Validation Experiment

The participants of this study had multiple questions of clarification or understanding and occasionally misinterpreted the description and depiction of the presented light patterns. These problems disappeared when SMALLCAR was used to show the respective light patterns. Adding to this, SMALLCAR conveyed information about parameters easier, such as brightness, color, transitions, or movement of light. This information was barely taken into consideration when judging the pattern based on the description and only became apparent when confronted with the implementation in SMALLCAR. According to the participants, the sensorbox and remote control gave the feeling of being in control and allowed easy manipulation of the mocked-up traffic situation. The identified issues of SMALLCAR included not actually using peripheral vision during user tests, a rough looking installation of the light displays, missing visual feedback about the current state of the prototype and a missing user interface for non-programmers. All participants could see themselves using the SMALLCAR in the future.

6.1.6 Summary

SMALLCAR is a prototype that can be used to design and test in-vehicle light patterns in a sufficiently realistic setup. The prototype received positive feedback in both experiments: participants enjoyed using it to creatively explore the design space but also found it to be easier to find issues of an existing light patterns.



(a) One of the early prototypes made out of cardboard.

(b) The first functional prototype.

(c) The resulting prototype used in the experiments.

Figure 6.3: The PIVLD prototypes. The early ones were vertical prototypes, testing how the connection of the modules could work or how the modules can be programmed.

We used this tool several times to demonstrate light patterns that are discussed in this dissertation. However, more research needs to be done to validate if it is indeed a suitable tool to explore designs.

6.2 A Portable In-Vehicle Light Display

After the development of SMALLCAR (see Section 6.1), we were interested in a prototype that is not integrated into a car mock-up. This would help us to demonstrate and discuss light patterns inside any vehicle. Despite having a realistic environment, it will also be easier to try different locations. In this section, we present PIVLD, a Portable In-Vehicle Light Display that can be attached in the interior to display light patterns.

6.2.1 Ideation

Our goal is to develop a prototype that can be attached inside any car to display light patterns. With these requirements in mind, we first generated ideas on how to implement PIVLD with LoFi prototypes, such as the one shown in Figure 6.3(a). Our approach is to use modular parts that can be connected and are controlled via an easy to program Arduino with power supplied either by a car's 12V power supply, or battery packs. After we decided on this approach, we created a first working prototype as shown in Figure 6.3(b).

We invited seven experts for ALDs from our lab to answer a questionnaire about specific design challenges like the minimum set of locations in the car we need to support, how flexible the prototype needs to be, and how to connect the modules. In summary, the flexibility was rated to be a very important factor to be able to place PIVLD anywhere. While not deemed necessary, depending on the light pattern it may be important to have modules of different lengths. Mostly in line with the results of Section 4.1, the most important locations seem to be between A- and B-pillar, at the steering wheel, at the dashboard, along the A-pillar, and along the C-pillar.

6.2.2 Realization

We implemented the PIVLD utilizing several short LED-strips that can be plugged together. Each module is surrounded by semi-transparent foil to make the individual LED stick out less and make it less glaring. Each LED (not just each module) can be addressed individually. The first module needs to be connected to the Arduino that is used to control the light pattern. We equipped some of the PIVLD modules with Velcro or suction cups to be able to attach them to the interior of a car. Another simple way to attach the modules is using double-sided adhesive tape. The implemented prototype is shown in Figure 6.3(c) and Figure 6.4.

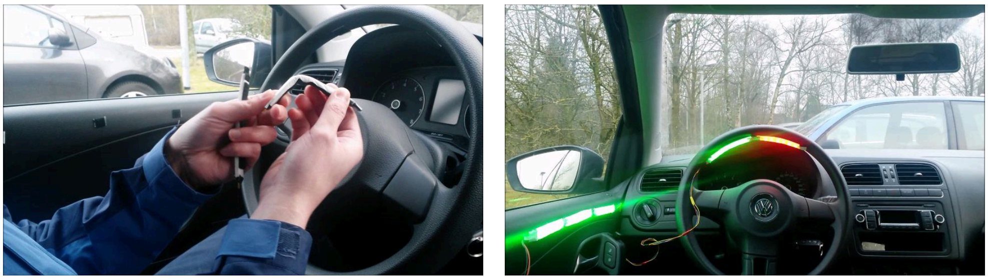
We conducted a small usability study with six participants (three ALD experts, three drivers). The study took place inside a VW Polo. We asked participants to attach the display at several locations and start a light pattern. Participants did not experience it as difficult to attach the modules. However, the suction cups did not work well, and the Velcro did stay intact throughout many experiments.

While this implementation fits the minimum requirements, we would like to use another shell for the LED-strips and a way to connect the modules without creating gaps between them to make them more similar to the prototypes used in our driving simulator, such as the one discussed in Section 3.3.3.

6.2.3 Experiments

We were interested in assessing if PIVLD can be used by developers to get early feedback for a light pattern without needing to invite participants to a lab. Currently, the typical way to present light patterns for early feedback is to show videos to participants. Hence, we conducted a study with 10 participants (5 female) and a mean age of 24.8 years (SD: 3) to compare video and PIVLD based discussion of light patterns.

The participants were divided into five groups. In each group, one person was assigned to the role “experimenter” and one to the role “driver”. Following a counterbalanced within-subjects design, all groups participated in both conditions: reviewing a light pattern using a video and reviewing it using PIVLD. The task of the “experimenter” was



(a) PIVLD is modular and can be extended to be as long as needed.

(b) Example application for PIVLD.

Figure 6.4: PIVLD in action. The challenge was to create a display that is flexible enough to be placed in most locations, but robust enough to be used reliably. In the example (b), we placed a part of the display at the door and a part at the steering wheel to discuss if this is a way to indicate a free gap to the left.

to conduct a study that was prepared by us to assess the weaknesses of a prepared light pattern that was presented to the "driver". The task of the "driver" was to read a text in front of him or her (to simulate driving) and count the number of cars passing by as displayed by the light pattern. We did not store or evaluate the "driver's" performance. After the experiment, we asked the "experimenters" several questions like how likely they would use the video-based and PIVLD based method for a real study. Similarly, the "drivers" were asked questions like how easy it was to assess the quality of the light pattern based on video and on PIVLD. We asked all participants to give three benefits and three drawbacks of using videos and using PIVLD.

In summary, it seems like the participants would prefer to use PIVLD over videos as the prototype is more realistic. According to the participants, the main benefit of PIVLD is the more realistic environment that also makes it possible to test patterns addressing peripheral vision. Other benefits include that it is easy to attach, that patterns can be changed quickly, and that test environments (cars) are more accessible. The most mentioned drawback is that the system could be more realistic, e.g., by driving during the test or equipping a driving simulator. Further, it was mentioned that the attachment could be better.

6.2.4 Summary

Complementing SMALLCAR, PIVLD is another way to demonstrate in-vehicle ambient light patterns without having to rely on a driving simulator while being more realistic than, e.g., sketches or videos. While the presented work is only a prototype and several improvements, like a "gap-free" connection of the modules, need to be implemented, the first user studies are promising.

6.3 Adapting to Frustration

Negative affective states such as frustration may lead to aggressive behaviors and have negative consequences for the experienced comfort of drivers. Hence, an affect-aware system which can recognize the current affective state of a driver and react to it appropriately may be able to support the regulation of emotions and to prevent negative consequences. Although this problem is not directly connected to the research questions of this dissertation, adapting to the driver's state can influence driving performance (RQ2). In this work, we report the results of a workshop with five human factors experts. Besides the presentation of the ALD concepts below, we also discussed how frustration might be measured in the future in [LIU17].

6.3.1 Motivation

Frustration is an aversive affective state that occurs when goal-directed behavior is blocked [Laz91]. Experiencing frustration can lead to aggressive behavior towards other traffic participants, which is thought to be the cause of a large share of crashes [Mar97]. Furthermore, frustration affects perceived stress [Edw16]. It is therefore preferably prevented. However, there are several sources of frustration in the car, such as blocking events during traffic (e.g., traffic jam) and delays when interacting with infotainment systems. Hence, drivers cannot avoid frustration entirely.

To tackle the motivated problem, the idea is to design machines that are capable of recognizing emotions, such as frustration, which can react to it, and support drivers regulating their current emotion. For such affect-aware systems, it is necessary to recognize frustration reliably and in real-time as well as to find appropriate interaction strategies to mitigate frustration. Recent studies have revealed that biosignals and non-verbal behaviors such as facial muscle activity [IDFJ18, GYT14, HKGV11] and brain activation patterns [IURJ18] could be indicative for frustration and thus be used in an affect-aware system. Hence, together with the scientific progress in machine learning, it appears realistic that future cars could become capable of recognizing frustration.

Only a few studies have investigated and implemented interaction strategies that successfully mitigate frustration. It was shown that the reappraise down strategy reduced the participants' negative affective state (e.g., [HN11]). Other studies used a social strategy to modify the situation via an active listening technique to support users and reduce the level of frustration [Hon06, KMP02]. Similarly, another study employed different etiquette strategies that reduced the frustration of users in HCI [YD16]. However, these studies have not been accomplished in a vehicle. Another interesting study applied light of a certain frequency to reduce the fatigue of drivers and increase drivers' positive affect [PFWR10]. However, it did not target frustration in particular.

So far, a small number of ideas for in-vehicle interaction strategies targeting frustration reduction have been reported. Therefore, our goal is to explore interaction patterns that can adequately react to frustration to positively influence the affective state and the behavior of drivers. For this, we chose a qualitative approach and conducted an expert workshop with human factors experts. The idea generation process was driven by three scenarios that were defined beforehand. The scenarios were selected so that they included different situations of frustration induction and different levels of automation.

6.3.2 Scenarios

Before the expert workshop, three application scenarios of a frustration mitigation system were defined to serve as a starting point for the discussion (see Figure 6.5(b)-6.5(c)). These scenarios address on the one hand the goal to increase safety by lowering the chance of frustration causing worse driving behavior (e.g., aggression) and on the other hand the goal to reduce discomfort caused by frustration.

6.3.3 Participants

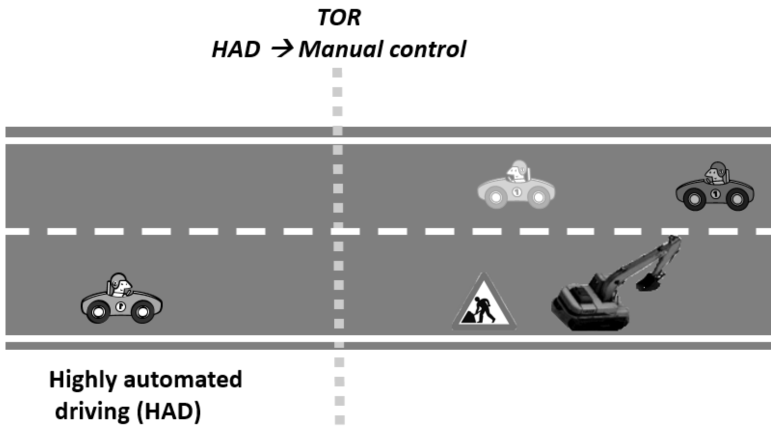
Five male human factors experts participated in an expert workshop (including us). Three experts had a background in computer science and human-machine interaction, one had a background in brain-computer interfacing and neuroscience, and one had a background in automotive human factors.

6.3.4 Procedure

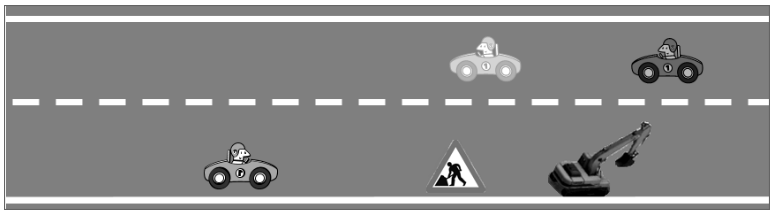
The workshop began with an introduction to the goal of the research. We further provided an overview of frustration in vehicles, previous work, and theoretical considerations. Afterwards, the three scenarios were presented and discussed. Every expert generated as many strategies as possible to reduce frustration for the scenarios. The ideas were jotted down on sticky notes that were stuck to the corresponding scenarios, each represented by a different flip chart. Each expert went on to explain his strategies and added new ones that were generated during the discussion. This was followed up by summarizing the minutes of the discussion and closing remarks. The whole procedure took about two hours.

6.3.5 Results of the Expert Workshop

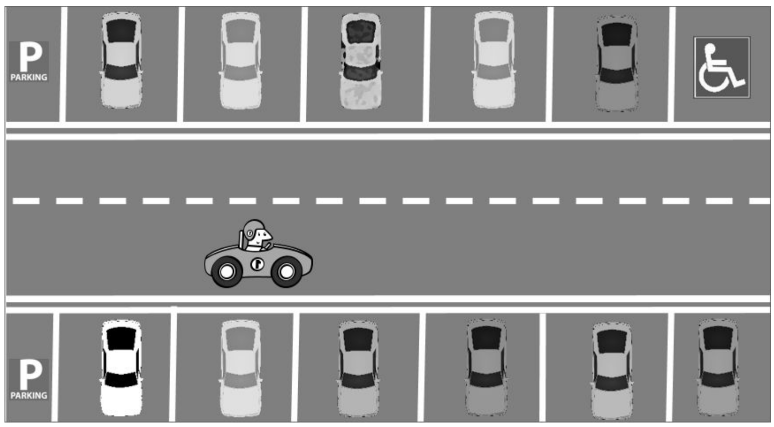
In total, 23 ideas for adaptation strategies were generated for the three scenarios. Eleven of them were related to the scenario “packed city”, seven to “TOR” and five to “no parking space”. The generated ideas for the “packed city” scenario were diverse and ranged from assistance or automation to mitigate the effect of frustration, interaction strategies to change the cognition about the situation, regulating the experienced frustration,



(a) Scenario "TOR": Before a construction site which the automation cannot handle, the driver is asked to resume control. However, at that point the driver is already frustrated (e.g., due to malfunctioning of infotainment system).



(b) Scenario "packed city": The driver is on the way to an urgent meeting, but the streets are full due to construction sites and lots of traffic so that driving at the preferred speed is impossible leading to frustration.



(c) Scenario "no parking space": The driver is frustrated because s/he cannot find an empty parking space in a parking lot.

Figure 6.5: Frustrating scenarios. These scenarios were selected as initial examples for frustrating situations during driving.

e.g., via biofeedback, to sharing the feelings socially. The ideas related to “No parking space” ranged from providing assistance that supports removing the source of the frustration (namely the lacking parking space) to regulating frustration via biofeedback. In contrast, the ideas for the TOR scenario targeted mitigation of the effects of frustration either by adapting the interaction strategy to communicate the TOR, or by supporting the driver after the take-over. In the following, we will list the ideas per scenario:

Take-Over-Request (TOR)

- Remind the user to do tasks that do not require 100% attention
- Adapt trigger of TOR
- Escalate trigger for TOR
- Extend the time to take-over
- Provide earlier TOR, adapted to the driver’s state
- Stabilize car after TOR
- Provide information about the situation early

Packed City

- Inform about the delay and whether the destination will be reached on time
- Handover control and let driver engage in other activity
- Play music or light to improve the state of the driver
- Explain the cause of the blocking events / provide a broader picture
- Reroute to less packed routes
- Biofeedback to reduce frustration
- Optimize trajectory to drive as smooth as possible and save fuel
- Socially share feelings
- Show how great area will look after construction
- Send automatic “I am delayed” messages to colleagues
- Reroute

No Parking Space

- Inform the driver about the number of free parking spaces
- The car takes over control to park and give the user time to do something else
- Automated solutions to find a parking space
- Communicate where the parking spaces are available
- Communicate in advance what time is good to park in that area

6.3.6 Concepts to Reduce Frustration

We derived concepts for an affect-aware in-vehicle system to reduce frustration based on the results of the workshop. All ALDs are designed not to be confused with warnings and thus avoid locations of warning displays and the use red color.

Biofeedback

Participants suggested feeding back the frustration level to the driver across all scenarios and argued that this could help to calm down a driver by making him or her aware of the frustration. Our concept is to place the display below the roof and illuminate the interior indirectly as shown in Figure 6.6. The intuitive red-green color mapping cannot be used because of the possible misinterpretation as a warning. Hence, we propose using a gradient from 'white' with low brightness for not-frustrated drivers to 'blue' with appropriate brightness for more frustrated drivers. These colors can be considered as neutral in the driving context, while the color blue may have a calming effect (e.g., [WR62, VM94]). Slow pulsating patterns can create a feeling of a more cozy environment as earlier research suggests (e.g., [WHL+12, WLL+14]) and could thus work against frustration. Hence, the proposed ALD pattern could also be a slow 'blue-green-pulse' where the brightness is mapped to the frustration level to increase the calming effect.

Take-Over-Request (TOR)

A common idea to support frustrated drivers was to adapt the TOR. Our concept is to adapt the ALD pattern proposed in the work of Sadeghian Borojeni et al. [SBCHB16]. Their results show that light cues can be effective in shifting attention to a take-over situation. One of the investigated ALD patterns uses lights that move from the center of the steering wheel to the side where a driver needs to steer to after the take-over. This ALD pattern may result in faster response times, compared to activating all lights on the corresponding side of the steering wheel. Expanding on this ALD pattern, the brightness can be increased, or the movement sped up to increase the ALD's saliency in (time-) critical situations for a frustrated driver. In non-critical situations, a TOR can be triggered earlier or with a less urgent pattern to not annoy an already frustrated driver.

Packed City

When in a hurry, blocking events such as red lights or construction sites can be frustrating. Two of the proposed ideas can be implemented with ALD patterns to reduce driver frustration in such situations: (1) encourage drivers to adapt their speed for an optimal get-through and (2) show driver how much time s/he lost, assuming that it is perceived to be more. The first idea (1) is already implemented, e.g., as *ChaseLight* [MDRT15]. Further, such a display does not need to adapt to frustration because it would prevent it. Our concept for the second idea (2) is a light display placed above the central console as

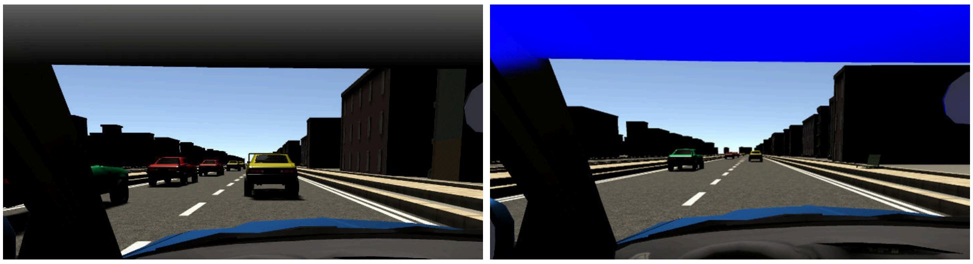


Figure 6.6: ALD on the ceiling for “biofeedback”. Left: not frustrated, right: very frustrated.

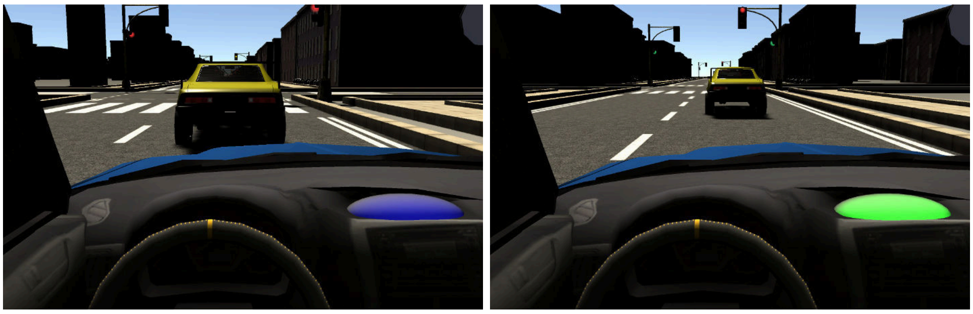


Figure 6.7: ALD pattern above the central console for “packed city”. Left: late but not frustrated, right: early but frustrated.

Figure 6.8: ALD pattern above the central console for “no parking space”. Left: few available slots, right: many free parking spaces.

shown in Figure 6.7. We propose using a color gradient which changes from ‘green’ for “arriving earlier than expected” via ‘white’ as a neutral color for “on time” to ‘blue’ as a calming color for “later than expected”. If the driver is frustrated but not late, the brightness can be increased to direct his/her attention to the fact that the delay did not have a negative impact. We argue that it is important to have neutral colors to not encourage the driver to speed up or get more frustrated because he or she is too late.

No Parking Space

A proposed idea to reduce frustration while searching for a parking space is to display the number of available parking spaces. This could help drivers to continue driving to another area with more parking spaces and not get frustrated by searching for a non-existing parking space. Just like the “Packed City” ALD pattern, we suggest placing the display above the central console (see Figure 6.8), but activate it only when the driver is searching for a parking space. A color gradient cannot be used because we already use that for the “packed city” scenario. Further, blinking or pulsating patterns could interfere with existing notifications and warnings and should be avoided. Hence, we suggest using the number of active LEDs to map the size of the ALD pattern to the number of available parking spaces. The full display is activated if sufficient parking spaces are available, while only a few LEDs would stay active otherwise.

6.3.7 Summary

In this work, we looked into three scenarios in which a system needs to adapt to a frustrated driver: driving in a “packed city”, before “take-over requests” in automated driving, and when unable to find a “parking space” in manual driving.

We conducted an expert workshop with five participants and identified 23 ideas on how to mitigate frustration. Based on these, we suggest four concepts for ambient light patterns for affect-aware systems which mitigate the effects of in-vehicle frustration.

It has to be noted that only two external experts participated (besides the authors of [LIU17]) and we only propose solutions based on ambient light.

6.4 Informing Passengers About Intentions of Their Automated Car

In the coming age of automation, drivers of automated vehicles will need to be assisted. First, because humans are bad at observing a system’s state over long periods, however, they will have to do so as long as they are expected to take over in certain situations (SAE Level 3). Second, because we assume that the operator’s trust and overall comfort will depend on the predictability of the car’s behavior and if the operator feels safe with its driving style, even with full automation (Level 5).

This dissertation focuses on manual driving. However, to get an impression on how drivers – or controllers and passengers – of automated vehicles can be supported (RQ2) with ALDs, we designed and implemented a display that communicates the short term plans, or "intentions" of the automation. This is not only relevant for Level 3 automation, where this might help operators to stay informed, but also in Level 4 automation and above, where the communication of the car's intention might increase the driver's trust. We also presented this idea in [LHB16a].

6.4.1 Motivation

Developing automated vehicles holds various challenges for designers and engineers. However, also the driver interface needs to change when drivers are no longer in control. As discussed by Casner et al. [CHN16], developers are facing several challenges. For SAE's Level 3 automation, one of them is "Increasing complexity". The authors explain that the automation will become complex and thus difficult to understand and monitor for the driver. Drivers have to restore the driving context as well as the vehicle's state "[w]hen they are unexpectedly asked to reassume control of the car, [and therefore] they are likely to struggle to get back 'in the loop' to assess the situation and be able to respond in time" [CHN16]. In order to help the driver to understand decisions of the automation and thus make it easier to assess the current driving situation when needed, we want to communicate the car's upcoming maneuvers, or "intentions". Helping to understand the automated car also remains relevant above Level 3 automation, as it might affect the driver's trust in the system.

For this work, we chose to use driving on a highway as a scenario because we believe it is likely to be the first driving context where automated driving will work reliably in the future. In this scenario, manually driving humans are assisted with several systems, as discussed in the previous chapters. These systems are designed with an active driver in mind. To complement these works and propose an alternative approach for the automated context, our goal is to give feedback about upcoming driving maneuvers to the driver instead of triggering warnings or displaying traffic participants. We believe that this will help the driver to understand the automation.

6.4.2 Requirements and Design Ideas

We interviewed seven drivers (three female) to look into requirements and design ideas. The interviews were semi-structured. These interviews took about 20 to 30 minutes and were in German.

First, we asked participants, what they would do while their automated car is driving. The answers were "Read" (3), "Use Smartphone / Laptop" (3), "Observe traffic" (2), or "Eat", "Drink", "Smoke", "Work", "Watch movies", "Sleep" or "Talk to other passengers" (all mentioned once).

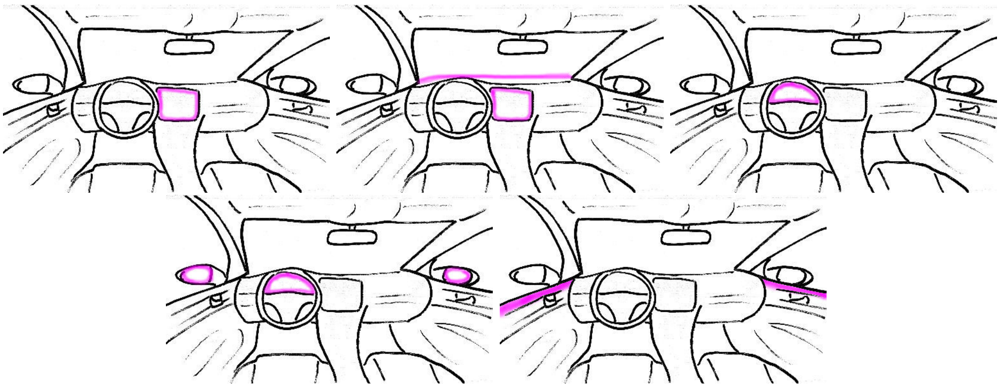


Figure 6.9: The resulting sketches (reproduced). The first sketch was created three times.

Afterwards, we introduced the participants to the following scenario and asked them various questions regarding a possible design: *»Imagine a system inside automated cars that announces the upcoming driving maneuvers using ambient light. This system should be unobtrusive and intuitive. Ideally, the driver should know what the car is going to do, even if he or she is busy doing something else.«*

When asked for the visibility of the display, two participants did only want to see it from the driver's seat, while the majority wanted to be able to see the light from the back-seats (4/7) or front-seats (5/7).

We then asked participants to draw "their" light display into a given sketch of a car's interior. The summarized results are shown in Figure 6.9. Four participants placed the display close to the central console. One of them also placed parts of the display on the upper part of the steering wheel and below the windscreen. Two participants proposed to use the dashboard, while one of them added light sources to the mirrors. One participant proposed to use the area between A- and B-pillar, i.e. at the door, below the windows, to display information.

We further asked the participants which maneuvers they would like to see communicated and asked for light patterns. The most often suggested maneuver was turning (6), followed by changing lanes (5), braking (5), overtaking (5), accelerating (3) and Adaptive Cruise Control (ACC) maneuvers (3). The proposed colors were *red* for braking, *orange* for a lane change or overtaking and *green* for acceleration, turning or ACC functions. Proposed patterns were *blinking* for braking and turning, *moving lights* for changing lanes or *no changes* for ACC maneuvers, while multiple patterns were proposed to indicate acceleration or planned overtaking maneuvers. The participants wanted to get the information two to five seconds before the maneuver. The only exception is *turning*, which should be indicated 300m ahead on the highway or 50m ahead in the city.

Figure 6.10: The implemented light pattern, embedded in the driving simulator. From top to bottom: accelerating, braking, changing lanes to the left.

6.4.3 Implementation of the System

Based on the interviews, we identified two ways to implement the assistance: (a) an iconic display using an RGB-LED Matrix at the central console, and (b) LED-stripes between A- and B-pillars on both sides or in front of the driver. We decided to implement the design using LED-strips first because it enables us to implement light patterns that display spatial information intuitively.

The participants proposed three ways to use the spatial dimension: place an LED-strip below the windscreen, equip the side-view mirrors with LEDs, or place LED-strips below the left and right windows. We decided to use the LED-strips at the doors because it is possible to create light patterns that move along the longitudinal axis. Still, the other locations may be worth investigating in the future.

To implement the light pattern, we used the driving simulator described in Section 3.3 with the prototype described in Section 3.3.3. Snapshots of the patterns are depicted in Figure 6.10. To indicate acceleration, the light patterns fill up from B- to A-pillars on both sides in a white color. Braking is indicating by red color, filling up from A- towards B-pillars. Turning is indicated using orange blinking lights on the full left or right LED-stripe. Initiating an overtaking maneuver or changing lanes was designed with the same pattern.

We ran informal tests with people from our lab to get the parameters right. The colors were set to not blind drivers. Their RGB-values are RGB(3.9%, 3.9%, 3.9%) for white, RGB(11.8%, 0%, 0%) for red and RGB(5.9%, 5.9%, 0%) for yellow. However, those values are likely to be different if other LEDs are used or the ambient lighting conditions differ from the ones in our lab. The filling up light patterns were implemented by first activating one LED after another every 18ms and then deactivating one LED after the other every 18ms. Therefore, the pattern can also be described as a chase light that has a maximum width of all LEDs and moves from A- to B-pillar for braking or B- to A-pillar for acceleration. The blinking patterns were implemented by activating all LEDs for 400ms, then deactivating them for 250ms, then activating them again and so forth.

6.4.4 Testing the design

We tested the usability of our design with six participants. Afterwards, we refined it and ran a small experiment to check if drivers can assess the car's intention.

6.4.4.1 Usability Test

After introducing the six participants to our driving simulator and the scenario, we let them get used to the simulator and its automation for two minutes. Afterwards, we continued the simulation for seven minutes without giving a specific task to them. Then we asked the drivers to read a book for another seven minutes. Then, they were asked to play a game on a tablet-PC for another seven minutes. During the experiment, the experimenter took notes. Afterwards, we carried out a semi-structured interview. Overall the experiment took about 45 minutes per person.

After analyzing the interviews, we clustered the responses into negative and positive aspects of the display.

Negative Aspects

The light patterns were perceived as *inconsistent* because not every acceleration or braking maneuver was signaled. Further, there was no signal if an announced lane change maneuver was canceled.

Another aspect was the missing *configurability* of the system. According to the participants, people would prefer to customize which maneuvers should be indicated and change detailed settings, such as at which expected brake- or acceleration force the system should inform the driver.

Positive Aspects

Overall, the light patterns were perceived as *intuitive* and *unobtrusive*. The participants also reported that they were *able to recognize* the information while reading or playing.

6.4.4.2 Redesign and Second Experiment

We did not change much of the design. To address the perceived inconsistency, we added one light pattern that displays aborted lane change maneuvers by using a slow fade-out of yellow light.

To get first impressions for the efficiency of our concept, we ran a second experiment using the same scenario as the one described above. In this study, the participants drove nine minutes with and nine minutes without the light display in a counterbalanced order. Further, the participants were not distracted. During each drive, an auditory signal was triggered ten times. The participants were asked to predict the next driving maneuver within one second, whenever the signal appears. We measured how often they predicted the next action correctly.

Six drivers participated. In total, 93.3% of the predictions were right with our prototype, while less than half (41.7%) of the predictions were right without the prototype. As the participants had to decide between four options, 25% would indicate random guessing.

6.4.5 Summary

Overall, participants perceived the light patterns as intuitive, but inconsistent because of missing information about aborted maneuvers. Further, the second experiment suggests that upcoming maneuvers seem to be much easier to predict with our light display than without it.

Its exploratory nature limits this work. The group of participants is too small to represent users reliably. Also, we did not distract participants in this experiment and effects may be different in a more realistic setting. Furthermore, the difference between different levels of automation may have an impact on the perceived usefulness of our system.

6.5 Summary

In this chapter, we presented two prototyping platforms that can be used to explore and discuss ambient light patterns easier than with the solutions we used in the other chapters. Developing these prototypes did not contribute much to the research questions of this dissertation, however, using them can help to develop new ambient light patterns and recognize issues early on, thus indirectly contributing to RQ1 and RQ2 in the future.

Further, we presented four concepts for ambient light patterns that mitigate frustration and realized one concept to communicate an automated car's intention to its passengers. The frustration aware light patterns showcase how we can apply the answers to RQ1 to develop new light patterns. However, they were realized inside a simulation, and not further discussed or validated.

The ambient light patterns for automated driving were developed to explore how ALDs can be used in a future where drivers are front-seat passengers and do not need to react quickly. It supports some results of our previous experiments concerning RQ1. The color red is used as a warning ("braking"). Yellow is used to indicate a lane change, in-line with current systems. Further, blinking and moving is used to make the passenger aware of an upcoming maneuver, while fading indicates an abortion of the intended maneuver. Longitudinal movement is used to indicate upcoming changes in velocity. With regard to RQ2, we observed that participants predicted the automated vehicle's intentions better than without assistance.

In short, this chapter gives examples of how ALD might be designed and used in future use cases that still have the human in the center, but not as driver. A vast number of use cases for in-vehicle ALDs has not been investigated yet and also our prototyping platforms need to be fully developed and validated to help exploring them in the future.

7 Conclusion

The goal of the presented research was to explore how ambient light can be used as a modality to assist drivers in potentially safety-critical situations. We identified three research questions: *Which Parameters of an ALD Can Be Used for Displaying Critical Information Inside a Vehicle?* (RQ1), *How Effective are In-Vehicle ALDs for Supporting the Driver?* (RQ2), and *How Do In-Vehicle ALDs Affect Gaze Behavior?* (RQ3).

The reasoning behind this research is that ALDs address peripheral vision and thus perceptual resources that are not as loaded as the ones addressed by common display modalities in current systems. We, therefore, expected a positive effect on the driver's performance, as he or she is assisted without being distracted – neither visually nor cognitively.

To explore the design space and therefore investigate RQ1, we reviewed how ALDs are used in common ADAS, looked into driver expectations towards ALDs located at different locations and developed five ALDs for distinct ADAS, following a human-centered design process.

Towards RQ2 and RQ3, we selected changing lanes on a highway as a representative for a complex and demanding driving situation. We evaluated the effect of ALDs on driving performance in four experiments, with two of them also looking into effects on the gaze behavior.

Finally, we present future research directions. One direction is the development of prototyping tools that facilitate faster or easier development and demonstration of light patterns. The other direction is applications for the future, displaying intentions of an automated vehicle to its passengers.

In the following, we reflect on the research questions, contributions, and discuss future work, before we conclude this thesis.

7.1 Research Contributions

The unique contribution of this work is its exploration and evaluation of ALDs in the vehicle that support drivers. While related works already indicate that light displays can be used to display information to drivers, this dissertation looks into the ambient aspect of ambient light display, focusing on addressing peripheral vision to convey information without demanding focused attention of a driver. In the following, we will present our research questions and summarize the contribution of this dissertation towards these questions.

7.1.1 Which Parameters of an ALD Can Be Used for Displaying Critical Information Inside a Vehicle?

Towards ALDs that can be used in the vehicle without distracting drivers, we need to understand which parameters contribute to an intuitive and effective light pattern. Together with other researchers, we identified guidelines for ALDs in general and summarized this research in Section 3.2. Further, we analyzed common encodings in automotive works that are using light displays to encode information (see Section 4.6). To complement these works, we ran exploratory studies as presented in Chapter 4. In addition, we summarized which parameters worked well when developing light patterns for LCDAS and other applications in the later chapters.

In summary, most participants suggest a traffic light metaphor to indicate safe or unsafe situations. However, we learned that this does not mean that light pattern designs are limited to displaying color in the range red-amber-green. For example, moving light cues can encode spatial information, blinking and pulsing cues attract the attention but need to be used with caution, and colors can show a status. The derived design recommendations are presented below.

Location of the Cue

One of the critical parameters of an ALD and its cues is the location. An intuitive light pattern should be located close to the line of sight towards the information it is referring to. Further, spatial information, like “turn left soon” or “approaching car on the rear left”, should be mapped on the location of the cue on the ALD.

Colors

Throughout the literature and own experiments, a red color is associated with warnings and should thus not be used to indicate anything else. Green color, on the other hand, is mainly used to indicate either a “good” status, like a safe gap. However, it is also interpreted as a call for action, e.g., “start the maneuver” like a green traffic light would suggest. Therefore, green must not be used in situations where the current state may be good, but in which drivers should only proceed with caution, as the encoding may be misunderstood. Yellow, amber, and orange are usually used to indicate a “caution”, or “get ready” state between green and red encoded ones.

The color does not seem to be important when there is no encoding of critical or safety-related information. In these situations, white, blue, and purple can be used as neutral colors to inform drivers, depending on the user’s preference or associations with the particular color in the given situation. For example, “blue” and “red” can be used to visualize “cold” and “hot”, but also “far away” and “close by”. Nevertheless, color is a parameter that can not solely be perceived via peripheral vision. Therefore, the encoded information should be considered as perceivable “in a glance” or “on demand” and not peripherally.

Size & Brightness

The size of the light source, i.e., the number of active LEDs, is commonly used to indicate a distance, or relate to the size of a displayed object. Furthermore, one way to increase the saliency of an ALD is to increase its brightness or size.

However, in every interview, participants were concerned that too bright lights may blind or distract a driver, passengers or other people. Also, many people pointed out that LED strips may not be bright enough to be noticeable in bright daylight conditions. We argue that lights can adapt to the relative ambient lighting around the display. Supporting this, we did not observe major problems in our two experiment outside of the lab (see Sections 4.3 and 6.2). However, changes in ambient lighting conditions and thus adapting brightness levels of the display may make it difficult to perceive intentional changes in the brightness level of a light pattern. Therefore, crucial information encoding should not rely on brightness.

Transitions / Temporal Behavior

The most important aspect about transitions between states is that they must be “smooth” to avoid distracting or annoying a driver. On the other hand, blinking or pulsating patterns can be used intentionally to get a driver’s attention quickly. Still, many participants pointed out that blinking patterns need to be restricted to important notifications.

When clearly distinguishable levels are needed, e.g., safe/unsafe gaps, drivers prefer distinct encodings, e.g., green/red color, with quick, smooth transitions, e.g., a 500ms color gradient. Continuous information, e.g., distance, can directly be translated into a gradient between the maximum and minimum of the expected values. Based on our observations, a continuous encoding seems to give drivers another source for necessary information but does not help them to decide faster as it does not recommend anything.

Furthermore, fast transitions or fast blinking and pulsing patterns were perceived as more urgent than slowly changing states.

Combining Parameters

Combining parameters to encode the same information can be confusing and needs to be evaluated. However, fast blinking red light, especially opposed to static green light is an example of a combination that stresses the dangerous or urgent nature of the “red” state.

7.1.2 How Effective are In-Vehicle ALDs for Supporting the Driver?

While RQ1 focused on how to realize intuitive light patterns for ALDs, this research questions aimed at the effectiveness of using ALDs to assist drivers. We realized ambient light patterns for several assistant systems (see Chapter 4) and focused on this question when evaluating ALDs for LCDAS (see Chapter 5.

The literature survey and exploratory works indicate that ambient light patterns can be designed to support drivers. Further, they can be designed to not distract drivers. However, we could also show that ALDs can improve driving performance. The ambient light based navigation device outperformed a GUI based one (see Section 4.2). Also, the results of our ALDs for LCDAS show that using ambient light can assist the driver. However, the first experiment for the LCDAS (see Section 5.1) also shows that driving performance can decrease if the light pattern is designed poorly.

In summary, our results indicate that ALDs can be used to assist drivers. However, although we saw improvements over solutions with GUIs, more research has to be done to assess when ambient light is more suitable than other modalities.

7.1.3 How Do In-Vehicle ALDs Affect Gaze Behavior?

One of the fundamental assumptions of this research is that ALDs are perceived via peripheral vision. However, this assumption was not validated, and many people were concerned that a light display may actually rather direct drivers' attention towards it and away from the current driving task, instead of helping them to receive the information in the periphery.

Blinking or quickly moving light patterns are known to grab the attention. However, our light patterns avoid sudden changes when the driver's attention should not be grabbed. Our gaze behavior analysis shows that using our patterns for the ALDs did reduce the drivers' need to focus to other locations than the traffic scene ahead. Taking the observed driving behavior into account, we conclude that crucial information was perceived with peripheral vision.

7.2 Limitations and Future Work

The research presented in this dissertation has several limitations. For example, we ran most experiments inside a driving simulator. Although simulators are commonly used in automotive research, the observed effects may be different in a real-world setup, as we discuss in Section 3.3. On top of that, we limited the control of drivers over their vehicle, thereby further limiting the realism of the simulation. Also, we did not test the influence of varying lighting conditions on the effect of our light patterns. Although testing different environmental conditions could have been technically feasible, we decided to focus on developing and testing light patterns for constant environmental conditions in order to keep the setup simple and the results comparable. Future work should, therefore, complement our research in more realistic driving simulator studies or outside the lab.

An aspect that we did not investigate is habituation. Most of our experiments were not long enough for participants to get used to a specific light pattern. Thus, we cannot know if the observed effects are still valid after a driver got used to the display. Long term studies should help to investigate this in the future.

The cultural background of a driver may play a role in the perception of our ambient light pattern. We did not control for the cultural background, and our participant pool consisted mainly of people living in Germany. Therefore, our experiments, or variations of them, can be repeated at other locations, like China, in which Western culture is not predominant. Similarly, the demographics of our participant groups do not reflect the demographics of the population. Future research needs to investigate, for example, effects of age on the perception of the ALDs.

Also regarding our participants, we did not study if the light patterns work for people with visual impairments or color blindness. In the future, it needs to be evaluated if the light patterns are suitable or can be refined for this target group without making it more difficult to understand for the majority, or if other light patterns or modalities need to be used.

Adapting the display to a model of the driver's uncertainty seems to be a promising approach for effective ALDs. Much more research can be done in this direction. For example, real-time adaptation to the driver's state based on brain imaging methods instead of models as we suggest in Section 6.3.

Another future research direction is the combination of ALDs with other modalities, such as vibration or sounds. For example, ambient light could be used in the early information and warning stages in which we do not want to distract drivers, while it could be combined with other modalities to escalate the warning or give more detailed information.

As we implied in the Sections 6.1 and 6.2, future research could also look into new ways to easier prototype and discuss ALDs in the early design phase. Looking at current trends, it will be interesting to see if the advances in virtual reality (VR) could enable researchers to test their early designs without implementing them into a prototype.

In the future, light patterns could also be individualized to account for driver preferences such as gap thresholds or colors for neutral information.

Finally, as introduced in Section 6.4, ALDs can not only support drivers but also assist passengers of automated vehicles to better anticipate its actions.

7.3 Concluding Remarks

This dissertation concludes that ambient light displays can be used to give drivers important information via peripheral vision. We proposed ambient light patterns for aiding in navigation, reverse parking, avoiding forward collisions, and changing lanes. We looked deeper into the lane change scenario and found that good ALDs make drivers maintain safer gaps and move their focus less often away from the forward road. Based on our results, we also derived design recommendations for future researchers and designers and suggested future research directions

The more we investigated, the more questions opened up. For example, “how will this influence older adults?”, “how do ALDs need to be designed for color-blind people”, or “will this work in the real-world?”. Further, the designs for our applications are often only iterated once and thus have much room for optimization. Considering current trends, the most interesting questions may be, “can this be used in automated driving?”, and “can we test ALDs in Virtual or Mixed Reality?”. This dissertation tries to give first results towards these questions where appropriate but there are many opportunities to extend on our results.

We conclude that in-vehicle ambient light displays can be designed to support drivers well in several use cases, and provide design recommendations for future researchers and designers. We believe that ambient light is a suitable addition to the available modalities to design driver assistance systems and thus can help to avoid overloading drivers. With ever increasing traffic density and distraction through brought in devices, it will be crucial to optimize displays of assistance systems to keep the number of accidents low. Even with automated driving on the horizon, we can see ambient light being used to give information to passengers and thus make them feel well informed.

Figures

Tables

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